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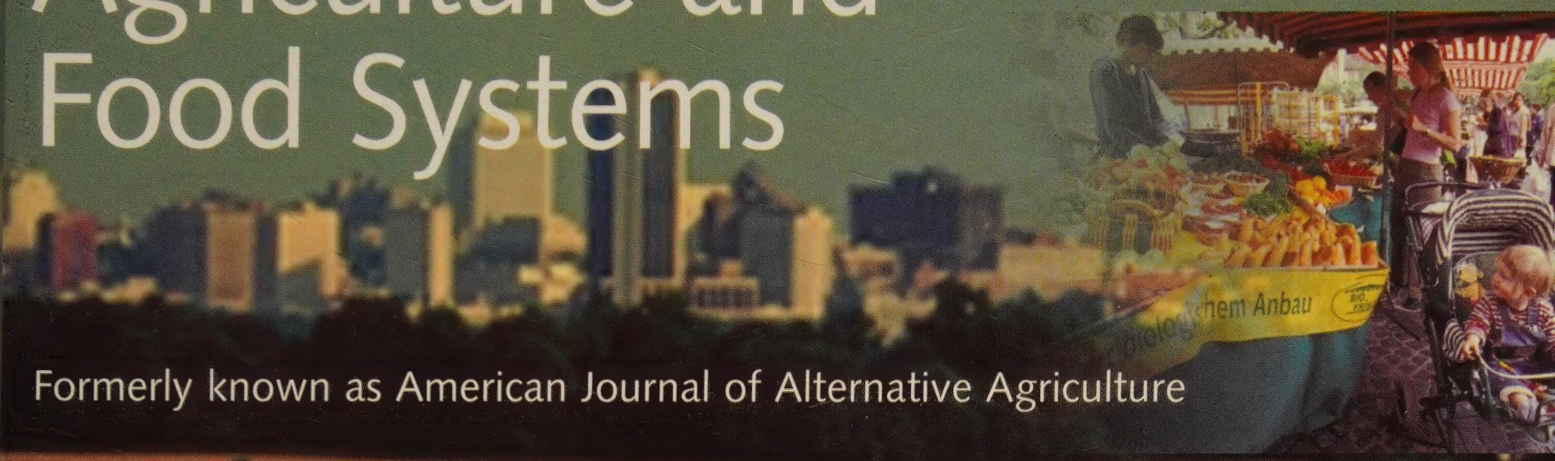

Special Issue

Researching Sustainable Agricultural Systems, ISOFAR 2005
Special Guest Editors:
Daniel Neuhoff, William Lockeretz & Martin Entz

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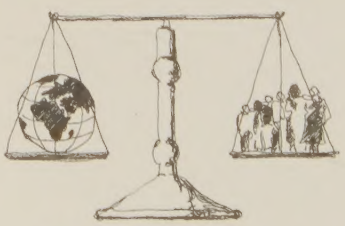

"Sustaining Earth and its People"

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Editorial: Exploring organic agriculture's place within the agricultural revolution

The 10,000-year-old agricultural revolution continues. However, the nature of this revolution has changed in recent years—at least a little. During most of the last century, agricultural progress was described by systems that produced more crop and livestock products through the addition of 'external inputs'. Organic Agriculture has become an alternative to the industrialized systems that now dominate much of world agriculture. The organic movement started with scientists, farmers and gardeners who noticed the benefits to food production systems that emphasize integration, recycling and diversity. Organic Agriculture is the most popular current example of regenerative agriculture[1]—where crop and livestock production are based on ecological principles[2]. By drawing on the resource-conserving aspects of traditional practices and the best modern ecological and agronomic knowledge, Organic Agriculture strives to meet the twin needs of sustainability and productivity. Today, Organic Agriculture is growing worldwide at both the production and consumer levels.

A great number of questions are being asked about Organic Agriculture. While ecologically based agricultural systems may sound good in principle, can they really advance agriculture—especially since they appear to reject the technologies that contributed so much to recent gains in food production? Is Organic Agriculture advancing the revolution, or is it just a counter-revolutionary distraction? These are important questions that deserve answers. Some answers to these questions are given in this special issue entitled 'Researching sustainable agricultural systems', based on selected short papers presented at the First Scientific Conference of the International Society of Organic Agriculture Research (ISOFAR) in September 2005 in Adelaide, SA, Australia.

Many agronomists question whether Organic Agriculture can provide high yields. 'How can farmers grow competitive crops without herbicides – especially in the face of so many weeds?' This is a legitimate question, especially given that we are still battling weeds in conventional agriculture after 50 years of herbicide use. Our ongoing 'war on weeds' has shaped the way industrial crop production is practised, and it has defined much of the way agronomists and farmers perceive weeds[3]. In this issue, Hauggaard-Nielsen et al. demonstrate that polycultures—intercrops of barley and legumes—enable crop plant communities to suppress weeds and suffer less disease, while at the same time maintaining productivity. This work clearly demonstrates that applying the basic ecological principles of diversity, competition and facilitation allows organic crops to be productive even in the face of pests. Also in this issue, Lukashyk et al. determined an optimum combination of plant competition and soil disturbance (tillage) for effective control of Canada thistle—one of Organic Agriculture's worst perennial weeds. This information will likely be music to the ears of researchers such as John Vandermeer, who has long since understood the ecological basis of alternative agriculture[4], but whose views have not always been appreciated by agronomists. The challenge for agronomists will be to design site-specific polyculture systems and management schemes that work in different soil, climate and crop systems.

Questions also exist about organic livestock production—especially regarding animal health. In this issue, Haring et al. tested tanniferous legume plants for nematode control in sheep. They identified legume species that provided both high pasture yield and parasite control. Their research showed that a plant-based therapy may be an alternative solution for parasite control in livestock—another fascinating application of ecology in the food production system.

Climate change and energy supply concerns are rapidly changing how we think about agriculture. It is doubtful whether Organic Agriculture will be spared. While it is well–documented that organic farms require 40–50% less external energy than conventional farms[5], little is known about how organic farms might become energy producers. In this issue, Halberg et al. identify the changes to land use and crop choice needed for a Danish cash crop farm to become more energy-independent through production of biodiesel from canola and biofuel from biomass. This study also raises new questions regarding the policy and infrastructure changes needed for such changes to occur in reality.

Environmental stewardship is just so important! For example, it is becoming clear that agriculture needs to be more answerable for greenhouse gas emissions. In this issue, Kustermann et al. present a detailed accounting of greenhouse gas emissions and energy use from organic and conventional farms. Their work was conducted using a modeling approach that considered C and N within soil–plant–animal systems. The Kustermann et al. paper provides an excellent example of how to conduct greenhouse gas balance studies on a whole farm basis, and it stresses the need for interdisciplinary research teams. Readers will

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find the results of this particular paper encouraging, and they will learn that the superior greenhouse gas balance for the organic farm is very much a function of the farming system type (organic mixed grain–livestock farm compared with conventional grain farm). A similar reason was given by Hole et al.[6] for greater overall biodiversity on organic compared with conventional farms—more evidence that functional diversity at the farm level is an important contributor to environmental sustainability.

It is notable that all of the papers in the 'Researching Sustainable Agricultural Systems' special edition are European. Perhaps this reflects the reality that Organic Agriculture research is more advanced in the European Union than in other countries. Organic farming and organic farming research have been well supported financially in Europe for over 20 years. In fact, in this issue, Zander et al. reflect on the financial relevance of organic farming payments to European farmers. Results of their study will be of interest to policymakers elsewhere who are considering how to encourage a sustainable organic agricultural sector.

Three volunteered papers from the USA were added to this special issue to expand the focus beyond only the European experience. The first paper, by Tanaka et al., deals with practical research considerations for, and barriers to, integrated crop/livestock systems research in the Northern Plains. In the next paper, Conner et al. highlight the promise of pasture-raised livestock products for reconnecting producers and consumers in the USA. The final paper, by Bell and Raczkowski, presents the importance of proper measurement of selected soil properties in assessing short-term changes in soil quality as affected by tillage, organic and successional fallow management systems.

We conclude that Organic Agriculture will contribute positively to the agricultural revolution. Organic farming systems are forcing us to better understand the ecological basis of food production systems and they offer hope for a healthy environment.

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Grain legume–cereal intercropping: The practical application of diversity, competition and facilitation in arable and organic cropping systems

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Abstract

Intercropping is the simultaneous cultivation of more than one crop species on the same piece of land and is regarded as the practical application of basic ecological principles such as diversity, competition and facilitation. Field experiments were carried out on a sandy loam soil and a sandy soil in Denmark over three consecutive cropping seasons including dual grain legume (pea, faba bean and lupin)–barley intercropping as compared to the respective sole crops (SC). Yield stability of intercrops (IC) was not greater than that of grain legume SC, with the exception of the IC containing faba bean. Faba bean and lupin had lower yield stability than pea and fertilized barley. However, the different IC used environmental resources for plant growth up to 50% (LER = 0.91–1.51) more effectively as compared to the respective SC, but with considerable variation over location, years and crops. The SC performance supported the interspecific interactions within the IC stand. On the sandy loam 13% greater grain yield of pea cv. Agadir (520 g m^{-2}) was observed as compared to cv. Bohatyr. Faba bean and lupin yielded similarly (340 g m^{-2}) in the sandy loam soil, with decreasing yields on the sandy soil (320–270 g m^{-2}). Nitrogen fixation was very constant in grain legume SC over species and location, varying from 13.2 to 15.8 g N m^{-2}, being lowest in peas and highest in faba bean and lupin. The intercropped grain legumes increased the proportion of plant N derived from N_2-fixation by on average 10–15% compared to the corresponding SC. However, especially lupin was suppressed when intercropping, with a reduced N_2-fixation from 15 to 5–6 g N m^{-2}. The IC were particularly effective at suppressing weeds, capturing a greater share of available resources than SC. Weed infestation in the different crops was comparable; however, it tended to be the highest in sole cropped faba bean, lupin and unfertilized barley, where the application of urea to barley reduced the weed infestation by around 50%. Reduction in disease was observed in all IC systems compared to the corresponding SC, with a general disease reduction in the range of 20–40%. For one disease in particular (brown spot on lupin) disease reduction was almost 80% in the IC. Intercropping practices offer many advantages but improved understanding of the ecological mechanisms associated with planned spatial diversity, including additional benefits with associated diversity, is needed to enhance the benefits achieved.

Key words: intercropping, grain legumes, cereals, yield advantage, resource use, nitrogen fixation, leaf diseases, weeds, grain quality

Introduction

Very often cropping systems are based on rotations of single genotype crops, although crop diversity is known to be a strong management tool[1]. Intercropping, planned diversity in space, defined as the simultaneous growth of more than one species in the same field[2] is the practical application of basic ecological principles such as diversity, competition and facilitation[3].

Intercropping including legumes is an old and widespread practice in the low-input systems of the tropics[2]. However, during the 20th century, farmers around the world replaced legume rotations and other traditional sources of nitrogen (N) with synthetic N fertilizers and

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Table 1. The experiments were carried out in three successive years during 2001–2003 at two different locations in Denmark on a sandy loam soil and a sandy soil. The soil characteristics have been examined on 0–20 cm topsoil samples.

Parameter	Sandy loam soil	Sandy soil
Place	The Experimental Farm of Copenhagen University	Jyndevad Experimental Station
Location	55°40′N, 12°18′E	54°54′N, 9°8′E
Soil classification (USDA)	8% clay, 32% silt, 48% fine sand, 13% coarse sand	4% clay, 4% silt, 17% fine sand, 73% coarse sand
Soil pH ($CaCl_2$)	6.8	5.5
Total soil C	1.7%	1.2%
Total soil N	0.12%	0.085%
Soil potassium	9.4%	3.8%
Soil phosphorus	3.6%	5.4%
Annual mean temperature	8°C	
Annual max. and min. temperature	16°C (July) and −1°C (February)	
Annual rainfall	600 mm	700 mm

increased use of pesticide inputs[4]. Today, the food and feed markets are experiencing increased awareness of environmental damage arising from the use of such non-renewable chemical resources, putting emphasis towards alternatives like organic farming. Organic crop production systems are commonly assumed to be more diverse than the conventional counterpart but that is not always the case. In temperate regions organic arable crop rotations consist mainly of sole crops (SC) (monocrops, pure stands) with the more diverse pastures being an exception[5].

Reported grain legume–cereal intercropping performance indicates some principal advantage worth considering while directing present agricultural practices in more sustainable directions like yield advantages and greater yield stability over years compared to grain legume sole cropping[5,6]. Furthermore, pea (*Pisum sativum* L.)–barley (*Hordeum vulgare* L.) dual intercropping compared to the corresponding sole cropping has shown a more efficient use of environmental sources for plant growth due to interspecific complementarity[7,8]. Special emphasis has been on N dynamics showing, for example, increased barley grain N concentration when intercropped with grain legumes as compared to the respective sole cropped barley[5,6,9] and higher percentage N derived from fixation (% Ndfa) in intercropped pea compared to sole cropped pea[6,10,11], but also increased competitive ability towards weeds has been highlighted[5].

Grain legumes such as field pea, faba bean (*Vicia faba* var. *minor* L.) and narrow-leafed lupin (*Lupinus angustifolius* L.) are valuable protein and energy source in human nutrition[12] and animal feeding[13]. Furthermore, grain legumes benefit the cropping system, contributing with atmospheric N inputs through biological N_2-fixation and recycling of N-rich residues[14]—a fundamental process for maintaining soil fertility in, for example, organic farming systems[15]. Other positive effects are disease break-crop effects[16] in the very often cereal-rich temperate cropping rotations.

The predominant cultivation of grain legumes under European temperate climates is sole cropping of pea. However, a major concern for farmers growing peas is the high degree of yield variability[17] due to drought sensitivity[18], lodging and weak competitive ability towards weeds[5,19]. Improved cultivars of faba bean and lupin might be alternative grain legumes to pea with a higher seed protein concentration and stronger stem strength but probably with the some of the same obstacles as peas, such as weak competitive ability towards weeds[20]. Intercropping experiments with faba bean and cereals have shown similar advantages[9,21,22], but knowledge of the effect of intercropping lupin and cereals for maturity is limited[23].

The main objectives of this three-year study were to determine the effects of dual intercropping of either pea, faba bean or lupin with barley in organic systems on yield performance, grain quality, N use, weed growth and diseases on two soil types in Denmark.

Materials and Methods

Location

The experiments were carried out in three subsequent years during 2001–2003 on a sandy loam soil and a sandy soil at two different locations in Denmark (Table 1). At both locations the soils have been cultivated for centuries and mainly cropped with cereals for the past four decades.

Experimental set-up

Field pea, faba bean and narrow-leafed lupin were grown as SC and in a two-species intercrop IC with spring barley. The field pea cultivars used were cv. Agadir, a semi-leafless cultivar with tendrils, relatively tall with a weak tendency to lodging (named pea A in tables and diagrams) and cv. Bohatyr, with normal leaves and medium stem strength (named pea B in tables and diagrams). The faba bean cv. Columbo had a low content of tannins and medium to early

maturity. The lupin cv. Prima had a relative early and uniform ripening caused by a highly reduced branching structure, where the upper main stem branches are reduced to a single floret in the axil of the main stem leaves. The two barley cultivars were cv. Lysiba, a low to medium yielding cultivar with a high content of the amino acids lysine and threonine (named barley L in tables and diagrams) and cv. Otira, a high yielding cultivar with low protein content (named barley O in tables and diagrams). Both barley cultivars had weak proneness to lodge.

The experimental plots (15 m^2 on the sandy loam soil and 36 m^2 on the sandy soil) were laid out in a complete one-factorial randomized block design with 16 treatments of IC and SC and four replicates. The dual IC design was based on the replacement principle, with mixed grain legume and barley grain sown in the same rows 12.8 cm apart at relative frequencies of 50 : 50. The rationale of the replacement design is that the interactions between IC components are not confounded by alterations in the plant density in the IC compared to the SC[24]. Target plant densities in SC of 300, 120, 90 and 40 plants m^{-2} for SC of barley, lupin, pea and faba bean, respectively, were in general achieved and the IC plant ratio of 50 : 50 was successfully obtained at both locations. Likewise, in the additional disease trials including three- and four-component IC in the respective 33 : 33 : 33 and 25 : 25 : 25 : 25 replacement ratios plant density and relative proportions were successfully established.

Management practice

The soils on the two locations contained efficient populations of native *Rhizobium leguminosarum* bv. *vicia* for the pea and faba bean symbiosis to work, whereas the lupin seeds were inoculated with an approved commercial *Bradyrhizobium lupini* strain just before seeding. Seeds were sown mixed in the rows in the same depth (3–5 cm) in early spring on both locations. The crops were grown according to organic agricultural management practice, except that the half of the barley SC was fertilized with 50 kg N ha^{-1} in urea. A false seedbed was established prior to sowing on both locations. Mechanical weeding was performed on the sandy soil.

Sampling and analytical methods

Leaf diseases were monitored throughout the experimental growth season, and whenever diseases were observed successive samplings for relevant disease were established using standard protocols.

The crops were harvested at physiological maturity. The plots were harvested manually (1 m^2) and separated into three fractions, i.e. grain legume, barley and weeds. The plant samples were dried at 70°C to constant weight and total dry matter (DM) production for each plot was determined separately for grain legumes, barley and weeds. After threshing, the grain DM yields were determined. Total N and ^{15}N content were determined on 3–15 mg sub-samples of finely ground material using an elemental analyzer (EA 1110) coupled in continuous flow mode to an isotope ratio mass spectrometer (Finnigan MAT DeltaPlus).

Calculations and statistics

Combined IC yield is the sum of yields of both the components in the IC. The land equivalent ratio (LER) is defined as the relative land area growing SC required to produce the yields achieved when growing IC[2].

$$L_A = \frac{Y_{A,IC}}{Y_{A,SC}}, \quad L_B = \frac{Y_{B,IC}}{Y_{B,SC}}, \tag{1}$$

LER for an IC of crop A and crop B is the sum of the partial LER values for crop A (L_A) and crop B (L_B).

$$\mathrm{LER} = L_A + L_B, \tag{2}$$

LER values >1 indicates an advantage from intercropping in terms of the use of environmental resources for plant growth compared to SC. When LER <1 resources are used more efficiently by SC than by IC.

The ^{15}N natural abundance (NA) method was used to estimate leguminous symbiotic N_2-fixation and calculated as the product of shoot N (grain legume biomass × % N content) and the percentage of plant N derived from fixation (% Ndfa). The percentage of plant N derived from fixation was determined as[25]:

$$\%\,\mathrm{Ndfa} = \frac{(\delta^{15}N_{\text{reference plant}} - \delta^{15}N_{\text{legume}})}{\delta^{15}N_{\text{reference plant}} - B} \times 100. \tag{3}$$

The B value is a measure of isotopic fractionation during N_2-fixation[26]. In the present study, B values were estimated for each grain legume species by analysis of the $\delta^{15}N$ of shoot N of nodulated pea, faba bean and lupin grown in N-free media[9,27]. The $\delta^{15}N$ values are the ^{15}N abundance relative to atmospheric N_2 ($^{15}N_{atmos}$) expressed as parts per thousand, calculated for each sample of the legume and the reference plant[25].

$$\delta^{15}\mathrm{N} = \frac{(\mathrm{atom\%}\ ^{15}\mathrm{N}_{\mathrm{sample}} - \mathrm{atom\%}\ ^{15}\mathrm{N}_{\mathrm{atmos}})}{\mathrm{atom\%}\ ^{15}\mathrm{N}_{\mathrm{atmos}}} \times 1000. \tag{4}$$

The NA method relies on differences in natural ^{15}N enrichment in soil N compared to atmospheric N_2 and reflected in $\delta^{15}N$ value of the non-fixing reference plant. The respective barley SC for each replicate was used as the reference plant using an average of $\delta^{15}N$ of the two barley cultivars.

Nitrogen balances for crops were determined to evaluate the net effect on the soil N pool when growing grain legume–barley IC as compared to the corresponding SC.

$$\begin{aligned}\text{N balance} = {} & \text{applied N} + \text{N}_2\text{-fixation (including} \\ & \text{below-ground N)} - \text{grain N export.}\end{aligned} \tag{5}$$

Fixed N positioned in below-ground plant parts for each grain legume species was included assuming that 15.6, 17.2 and 18.6% of total N accumulation in pea, faba bean and lupin, respectively, was present in below-ground plant

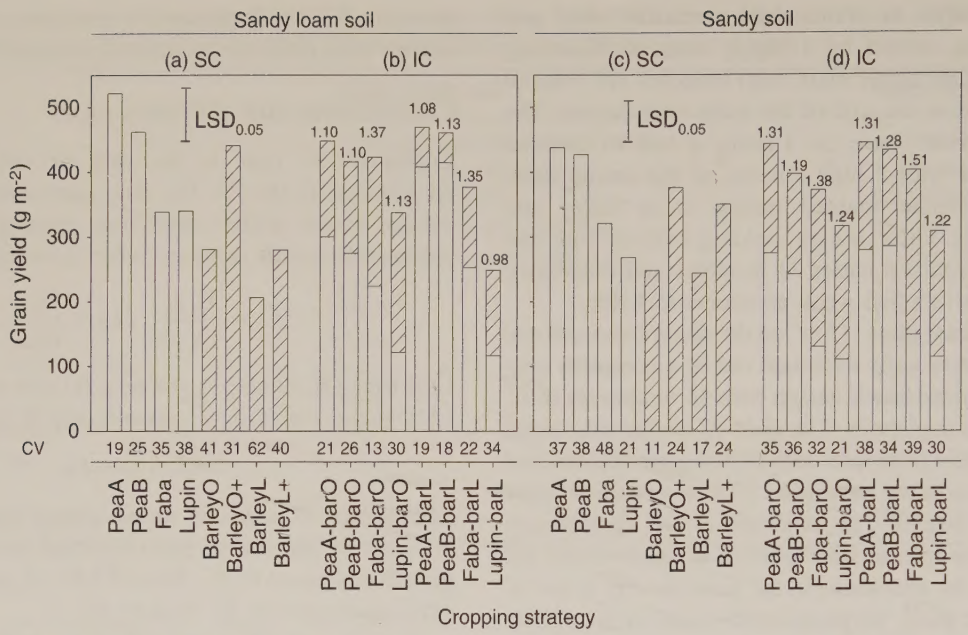

Figure 1. Average grain yields, yield stability [indicated below the *x*-axis as % CV (coefficient of variation) on average yields] of SC and IC of two pea cultivars (Agadir; peaA and Bohatyr; peaB), two barley cultivars (Otira = O and Lysiba = L), faba bean (Columbo) and lupin (Prima), grown in a sandy loam soil and a sandy soil during 2001–2003. Measures of intercropping advantage estimated using the LER are given on the top of IC bars. $LSD_{0.05}$ between cropping strategies is given by floating bars.

parts[28]. When calculating the amount of fixed N_2 positioned in roots the percentage below ground was corrected for the actual % Ndfa in the specific treatment.

Analysis of variance on plant samples was carried out using the GLM procedure of the SAS software[29] and probabilities equal to or less than 0.05 were considered significant. Assumptions of normal distribution and variance homogeneity were tested graphically using residual plots. Additional statistical analysis was conducted when evaluating disease data, including the Kruskal–Wallis test.

Results and Discussion

Grain yield and N use

A fundamental aspect of intercropping is to avoid unfavorable intra- or inter-specific competition possibly including interspecific facilitation[30], where plants increase the growth and survival of their neighbors[2,31,32]. LER ratios varied between 0.98 and 1.51 and indicate complementarities within the present grain legume–barley IC combinations[2,31], but with considerable variation over location, years and crops (Fig. 1). Combined IC grain yields were comparable to grain yields of sole cropped pea, but significantly greater than sole cropped lupin, faba bean and barley yields (Fig. 1). In descending order, the greatest grain yields were obtained for IC containing pea, faba bean and lupin. Pea was the dominant IC component on both soil types with no significant difference between cultivars. Faba bean dominated in the IC on the sandy loam soil, but not on the sandy soil. Lupin was suppressed by barley at both locations.

The SC performance supported the interspecific interactions within the IC stand with grain yields of the tested semi-leafless pea cv. Agadir of $520\,g\,m^{-2}$ in average over the 3 years on the sandy loam, 13% more than the normal leafed pea cv. Bohatyr. On the sandy soil there was no effect on choice of pea cultivar when sole cropping, averaging grain yields of $430–440\,g\,m^{-2}$, but with higher general pea–barley LER values due to lower barley yields (Fig. 1). When yields of IC exceed the yield sum of the component species grown alone[2], it is often as a result of better use of available growth resources [8,32,33] typically controlled by the level of interspecific interactions and the corresponding SC yields. It has been inferred that the trend of LER in legume–cereal IC was associated with the yields of the legumes[31], possibly due to the reputation of especially grain legumes having high yield variability[15,34,35]. However, in the present study, the weaker interspecific competitor was sometimes the grain legume and sometimes barley depending on crop combination and soil type, which means that it is not a species phenomenon. It may just be the growth of the weaker component that is determining the yield efficiency of the IC combination.

Faba bean and lupin had both a yield of $340\,g\,m^{-2}$ in the sandy loam soil, with decreasing yields of 320 and $270\,g\,m^{-2}$ on the sandy soil, respectively. However, especially faba bean showed a high degree of complementarity when intercropped, with LER values between 1.37 and 1.51, indicating up to 50% better utilization of the environmental sources for plant growth by the IC than by the corresponding SC. Faba bean might be a better choice than pea due to better spatial or temporal complementarity towards the barley companion crop, leaving space for both

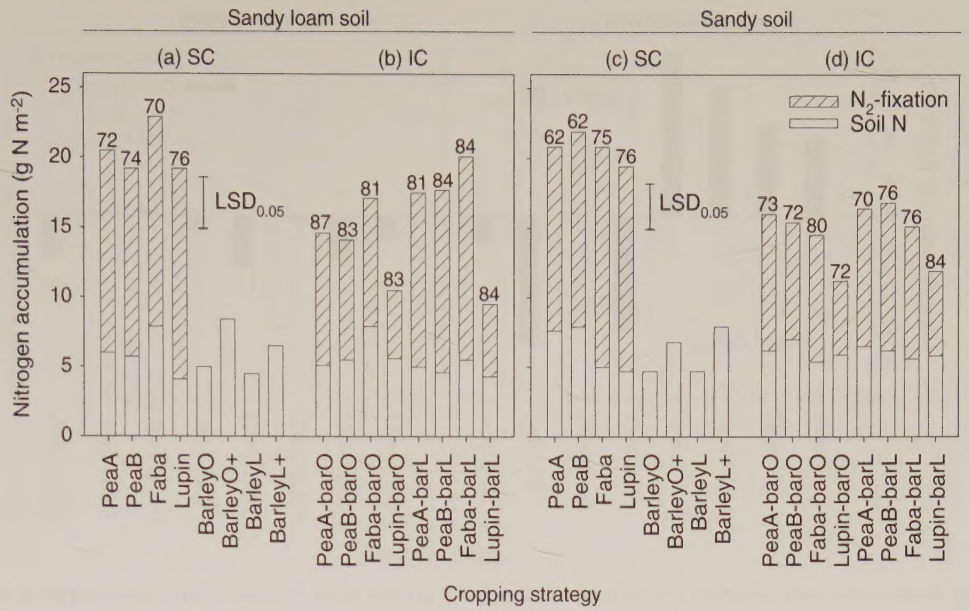

Figure 2. Total above-ground nitrogen (N) accumulation in SC and IC of grain legumes and barley partitioned in crop soil N, and leguminous symbiotic N_2-fixation at two separate locations during 2001–2003 (for further information see Fig. 1). Measures of percentage of N accumulated in above-ground grain legume originated from fixation are given on the top of bars. $LSD_{0.05}$ between cropping strategies is given by floating bars.

crops to develop and thereby utilize available environmental growth resources. The yield of lupin on the sandy loam soil was the results of yields of 420, 430 and 170 g m^{-2} in years 2001, 2002 and 2003; the latter yield due to the inoculation with an ineffective commercial *B. lupini* strain. Lupin have the greatest protein content of the present grain legumes[36] and extraordinary ability to mobilize phosphorus[37], but when growing a species under environmental conditions without efficient populations of native symbiotic bacteria difficulties with appropriate inoculation are clearly a limitation for farmers[38].

In contrast to results from Jensen[6] yield stability of IC was not greater than that of grain legume SC, with the exception of the IC including faba bean. The grain legume–barley IC showed less or similar variability compared to at least one of the respective SCs (Fig. 1). When working in organic cropping systems evaluation of specific species and cropping strategies should be conducted as an integrated part of the organic farming practices. It is not always appropriate to continue with the general knowledge very often gathered under conventional growing conditions, such as robust and stable yielding cereals as compared to unpredictable and variable grain legumes. On the sandy loam soil the highest yield stability was actually observed for the peas, whereas the barley yield was very variable, especially at the low N level.

Faba bean and lupin had lower yield stability than pea and fertilized barley. In contrast, on the sandy soil the highest yield variability was observed in the pea cultivars and faba bean and the lowest in lupin and barley, where the application of urea-N increased the yield variation significantly (Fig. 1). Grain legume–barley intercropping might not be the highest yielding as compared to the yield of one of the corresponding SCs in a single year, but it can be regarded as insurance against the complex abiotic and biotic stresses influencing crop performance, especially in organic systems. Self-regulation within the IC stand caused by interspecific interactions[2] can have a compensation effect against temporal or spatial nutritional limitations and/or attack from pest and disease organisms reducing annual yield variability.

Despite accounting for approximately more than half of the total biomass production (Fig. 1) the grain legumes accumulated less soil N when intercropped than could have been expected from SC uptake (Fig. 2). However, the LER values for soil N uptake were all considerably higher than 1, indicating a better utilization of soil N sources by the IC than by SC (data not shown). In accordance with other reported work[5,6,9] barley obtained proportionately more of the soil N when intercropped (Fig. 2), indicating that barley has a greater competitive ability for inorganic N sources[5,6]. Likewise, after application of 5 g N m^{-2} the grain yield of barley was raised 40–50% at both locations independent of cultivar (Fig. 1). When an intercropped cereal is more competitive for soil inorganic N the legume is forced to rely on N_2-fixation[9,39,40]. The intercropped grain legumes increased their proportion of plant N derived from N_2-fixation by on average 10–15% compared to the corresponding SC (Fig. 2). Nitrogen fixation was very constant in grain legume SC over species and location, varying from 13.2 to 15.8 g N m^{-2}, being lowest in peas and highest in faba bean and lupin. In the IC the nitrogen fixation per area decreased with increasing barley suppression of the grain legume, and fixation was more reduced with barley cv. Otira than when intercropped with barley cv. Lysiba, and more for faba bean and

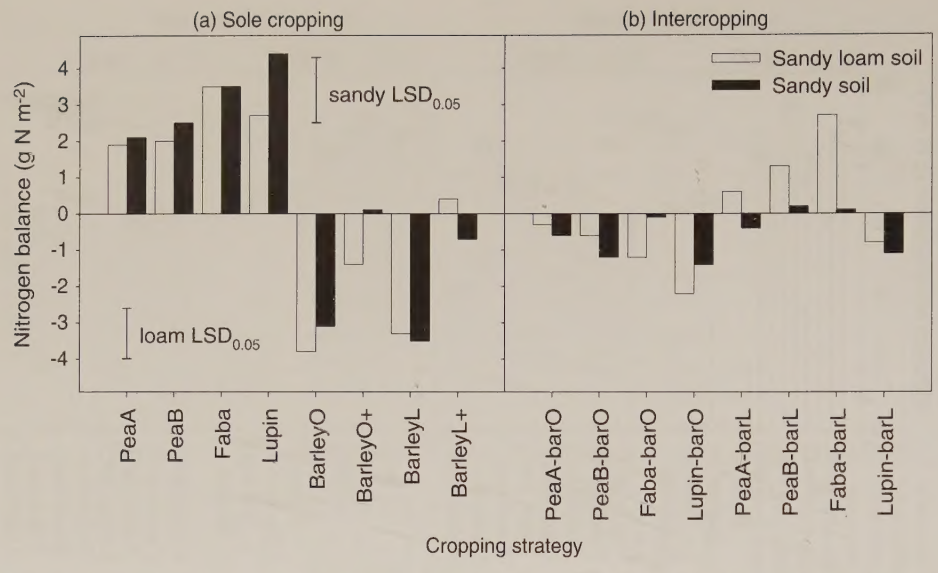

Figure 3. Nitrogen balance for each cropping strategy of sole cropping (a) and grain legume–barley intercropping (b) on a sandy loam soil and a sandy soil during 2001–2003 (for further information see Fig. 1). Balances were calculated according to equation (5). $LSD_{0.05}$ between cropping strategies is given by floating bars.

lupin than for peas. Especially lupin was suppressed when intercropping, with a reduced N_2-fixation from 15 to 5–6 g N m^{-2}. The interspecific interactions among the crops are delicate and specific to locations, and the growing of a certain IC combination may derive from several considerations such as: (i) more stable yields, (ii) N inputs to the cropping system and (iii) competitive ability towards traditional heavy weed infestation of a specific field, among several others.

Crop N balances were determined to evaluate the effect of cropping on soil N fertility. After subtracting N exported in the harvested grain crop, N balances were $+2\,g\,m^{-2}$ for both pea cultivars on both soil types and about $+3.5\,g\,m^{-2}$ for the faba bean and lupin. In barley, the crop N balances were all negative, ranging from, on average, $-3.5\,g\,m^{-2}$ on both soil types without urea-N application to near 0 after application of 5 g urea-N m^{-2} (Fig. 3). As the quantity of N in the harvested grain and the amount of fixed nitrogen is slightly lower for peas than for faba bean and lupin, the N balance is lower for the peas although still positive, meaning that grain legumes make a net contribution of N to the soil. When intercropping, a slightly negative balance was found except when faba bean was intercropped with barley cv. Lysiba on the sandy soil. The same trend was seen for the pea cv. Bohatyr. However, grain legume–cereal IC are not likely to increase soil inorganic N in the long term, but rather deplete it, although at a slower rate than in barley sole cropping.

Grain N concentration

The N content of grain legumes was highest on the sandy soil as compared to the sandy loam (Table 2) whereas the barley grain N content for the two soils went in both directions. The peas had an average N level of 3.6%, the faba bean 5% and the lupin 5.3%. A significant effect of the barley cultivar was noted where barley cv. Lysiba had a N concentration in the grain which was 0.2% higher than barley cv. Otira, and it responded to increased N level by a larger increase in grain N concentration compared to barley cv. Otira, which responded by a higher increase in total grain yield (Fig. 1). Competition from barley had little

Table 2. Grain nitrogen concentration (%) of sole cropped and intercropped grain legumes with barley at two locations during 2001–2003.

		Grain legume		Barley	
Cropping strategy	**Species[1]**	**Sandy loam**	**Sandy**	**Sandy loam**	**Sandy**
Sole crop	PeaA	3.27	3.73		
	PeaB	3.35	3.98		
	Faba	4.77	5.16		
	Lupin	4.94	5.67		
	BarleyO			1.43	1.36
	BarleyO +[2]			1.48	1.39
	BarleyL			1.61	1.51
	BarleyL+			1.66	1.71
Intercrop	PeaA + barO	3.15	3.84	1.80	1.64
	PeaB + barO	3.26	3.98	1.81	1.89
	Faba + barO	4.68	5.02	1.65	1.55
	Lupin + barO	4.72	4.9	1.42	1.72
	PeaA + barL	3.33	3.82	2.18	2.05
	PeaB + barL	3.34	3.97	2.15	2.14
	Faba + barL	5.10	5.19	2.00	1.65
	Lupin + barL	4.63	5.19	1.72	1.59
$LSD_{0.05}$		0.34	0.51	0.13	0.33

[1] For further information on species cultivars see Figure 1.
[2] The symbol + indicates application of 5 g urea-N m^{-2} to the barley sole crops.

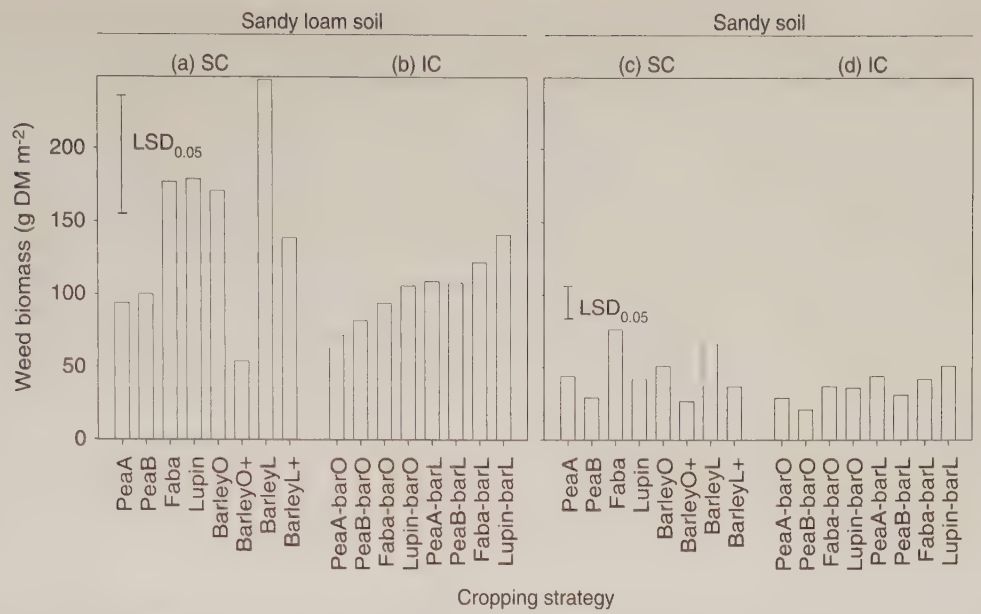

Figure 4. Weed above-ground DM production below grain legumes and barley sole cropping (SC) as compared to below grain legume–barley intercrops at two separate locations during 2001–2003 (for further information see Fig. 1). $LSD_{0.05}$ between cropping strategies is given by floating bars.

effect on grain legume grain N concentration despite a general reduced grain legume total N accumulation and increased proportion of N derived from fixation (Fig. 2). When barley was intercropped with pea significantly higher grain N concentration was found compared to the barley SC (Table 1), also when applying fertilizer N. On the contrary, faba bean only increased barley cv. Otira grain N concentration on the sandy loam whereas intercropped lupin did not influence measured barley grain qualities.

Grain legume–cereal interspecific competition can modify cereal grain N concentration[5,6] because grain legumes in general compete less efficiently for soil N sources. Relatively more soil N becomes available to the intercropped cereal as compared to the respective SC (Fig. 2). However, since grain legumes compete for other growth factors, such as light, water and non-N nutrients, cereals may not increase their yield in direct proportion to the amount of N available and an increased concentration of grain N can be observed. This is presumably the case for the present productive intercropped pea, whereas the less productive faba bean and lupin are not able to create enough interspecific competition towards growth factors other than N to raise barley N concentration (Table 1).

Other studies show how the N content of the wheat (*Triticum* spp.) grain increases when intercropped with faba bean[21,22]. From a recent study including intercropping of wheat with faba bean in Denmark, Germany, Italy and UK in both additive and replacement designs it was concluded that the increase in protein concentration of wheat grain in IC could be of economic benefit when selling wheat for breadmaking, but only if the bean crop was also marketed effectively[41]. Other cereal species such as rye (*Secale* spp.) or oat (*Avena* spp.) are also possible cereal IC components, depending on the specific target for the IC (grain quality, soil fertility, weed infestation level, etc.). Knowledge of the effect of intercropping lupin and cereals for maturity is limited[23], but the limited branching ability of the present lupin may reduce the ability to obtain sunlight which can translate into major competitive limitations[42] that strongly influence the interspecific competitive ability.

Competitive ability towards weeds

IC that are particularly effective at suppressing weeds capture a greater share of available resources than SC[19], which was clearly the case in the present study (Fig. 1). Any part of the soil surface that is not occupied by crop species is potentially subject to invasion by weedy species. Therefore, a typically more vigorous barley canopy structure as compared especially to faba bean and lupin in the present study provides a quicker, greater and more extensive soil coverage. A lower grain legume seeding density and initial growth rate, as compared to cereals[8], can fuel a rapid and intensive early weed resource uptake and thereby dominance throughout the rest of the growing season[43].

Weed infestation in the different crops were comparable; however, it tended to be highest in sole cropped faba bean, lupin and unfertilized barley, where the application of urea to barley reduced the weed infestation by around 50% (Fig. 4). Especially on the sandy loam soil considerable weed infestation levels were found within faba bean and lupin as well as barley, except for the fertilized barley cv. Otira which was able to suppress the weeds. The weed biomass on the sandy soil was one-quarter that on the sandy loam soil due to efficient mechanical weeding management and less infestation by volunteer red clover

Table 3. Diseases observed during the growth seasons 2001–2003 on the sandy loam soil and their percentage severity on the SC and median disease percentage reductions in disease in the dual intercrop systems (IC) as compared to the corresponding SC.

		Pea[1]		Faba bean		Lupin		Barley	
		Cropping strategy							
Diseases	**Year**	**SC[2]**	**IC[3]**	**SC**	**IC**	**SC**	**IC**	**SC**	**IC**
Ascochyta blight (*Mycosporella pinoides*)	2001	n/o	–						
	2002	9	−39*[4]						
	2003	10	−25*						
Chocolate spot (*Botrytis fabea*)	2001			n/o	–				
	2002			20	−24 ns				
	2003			22	−28 ns				
Brown spot (*Peronospora*)	2001					n/o	–		
	2002					3	−78***		
	2003					8	−87**		
Net blotch (*Pyrenophora teres*)	2001							25	−31*
	2002							20	−33*
	2003							25	−32**
Brown rust (*Puccinia hordei*)	2001							18	−18 ns
	2002							7	−28 ns
	2003							5	−23 ns

[1] For further information on species cultivars see Figure 1.
[2] The amount of disease observed when sole cropping (SC) in percentage leaf area covered.
[3] Median percentage disease reduction in the present dual IC.
[4] *, **, *** indicate significant differences ($P < 0.05$, 0.01, 0.001) from SC using the Kruskal–Wallis test. ns, indicates no significant difference.

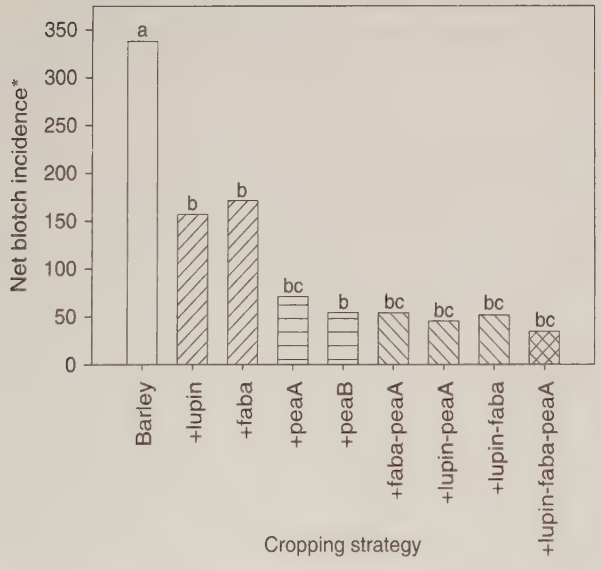

Figure 5. Effect of two-, three- and four-component IC of barley, lupin, faba bean and pea on incidence of barley net blotch (*Pyrenophora teres*) during 2002 when grown in the sandy loam soil. * Disease incidence measured as area under disease progress curve (AUDPC). Different letters indicate significant ($P < 0.05$) differences using the Kruskal–Wallis test. For further information see Figure 1.

(*Trifolium pratense*), which was a major problem on the sandy loam soil, especially in 2002. In general, the intercrops average the weed infestation levels in such a way that they are always lower than the levels of weeds in one of the IC component crops. This shows a more resilient crop stand able to respond to actual growing conditions as compared to grain legume sole cropping. Such a trait might be important to include as a management tool when the quantity and diversity of the weeds are high, as in the case of organic farming systems[44].

Effect on diseases

Components of IC are often less damaged by pest and disease organisms than when grown as SC, but this often varies unpredictably[16]. As an example, barley net blotch infestation levels are highlighted in Figure 5, as it was the most serious disease on barley during all 3 years. Interestingly, increasing the number of grain legume components reduced the amount of disease. As a general picture, reduction in disease was observed in all IC systems compared to the corresponding SC (Table 3). For all diseases (with the exception of brown spot on lupin) disease reduction was in the range of 20–40% (Table 3). Pathogens varied in dispersal mechanism and type (biotrophic or necrotrophic) and crops varied in height and anatomy. This suggests that there are mechanisms operating, possibly in all IC systems, whereby disease levels are reduced. However, for one disease in particular (brown spot on lupin) disease reduction was almost 80% in the IC. Furthermore, the well documented complementarity between intercropped barley and pea with respect to N[6,8,40] may in turn influence plant health[45].

To be able to predict which crop–disease combination would give the largest disease reduction, the mechanisms behind the disease reduction in IC must be understood, which was not possible during the present study. However, it is without doubt that under some conditions, intercropping can usefully contribute to the control of disease populations, but do the reductions in disease have any real effect on yield? This is a very difficult question to answer. We believe it is fair to say that if disease levels are high, then reduction in disease levels will have a greater effect on yield than if the initial disease levels are low. To test that, it is necessary to carry out specific yield experiments, where there is a disease-free control, which is impossible when working in organic farming systems.

Intercropping on the market

Most grain legume–cereal mixtures with similar ripening times are easy to combine-harvest using traditional on-farm equipment, but few buyers purchase mixed grains. Farmers are often left with the options of harvesting the mixture for animal feed. However, during the past 3–5 years a few Danish buyers working in the organic market have purchased mixed grains, often used for seed because of less damage from pest and diseases. The buyers charge 15–20€ per ton mixed grain for separation and cleaning, but when it is contracted for seed, a premium is given, making it profitable for the farmers to grow.

Grain legume–cereal intercropping is regarded as a cropping strategy based on the manipulation of plant interactions in time and space to maximize growth, with the possibility of increasing input of leguminous N_2-fixation into cropping systems and reducing the need for fertilizer N applications, and reducing pesticides due to improved competition towards weeds and less general damage by pest and disease organisms. Intercropping strategies offer a number of agroecological functions and services to the market, which are of increasing importance taking into account present environmental and energy issues on the global political agenda. Improved harvest technologies may in future make intercropping more attractive in the intensive agricultural areas of developed countries.

Conclusions

We conclude that the intercropping of arable crops has great potential in organic cropping systems. Intercropping may enhance and stabilize yields, reduce weeds and plant diseases and improve resource use. Improved understanding of the ecological mechanisms associated with planned spatial diversity, including additional benefits with associated diversity, will potentially enhance the benefits achieved from intercropping.

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Strategies to control Canada thistle (*Cirsium arvense*) under organic farming conditions

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Abstract

Three strategies for controlling *Cirsium arvense* including (i) repeated stubble tillage with subsequent forage crop cultivation, (ii) repeated mowing of a ryegrass–clover ley and (iii) forage crop cultivation following a ryegrass–clover ley ploughed in May/June were investigated in field experiments over 3 years at the Experimental Farm for Organic Agriculture 'Wiesengut' in North-Rhine Westphalia, Germany. The development of *C. arvense* (shoot density, shoot size and ground cover) was regularly assessed on fixed standardized subplots. In the medium-term (9 months), repeated stubble tillage (i) decreased shoot density and regrowth capacity of *C. arvense* more effectively than a mowed ryegrass–clover ley (ii and iii). However, after 22 months, strategies (i) and (ii) resulted in a similar strong reduction of *C. arvense* shoot density of 95 and 97%, respectively. At this time, the efficacy of strategy (iii) (89%) was not significantly different to that of strategies (i) and (ii). After 26 months, the effect of all strategies was still apparent; however, the efficacy of strategy (iii) was significantly lower than that of strategy (ii). Generally, the different strategies showed only minor differences, thus delivering options for optimal strategies of thistle control under given specific conditions of sites and cropping systems.

Key words: Canada thistle, stubble plough, wing share cultivator, mouldboard plough, tillage, ryegrass–clover leys, forage crop, mowing

Introduction

Canada thistle (*Cirsium arvense* (L.) Scop.) is an aggressive, colony-forming perennial weed. Due to the high adaptation and regeneration capability as well as wide environmental amplitude these plants occur mostly in all arable crops[1]. Once established, it is very tenacious and difficult to control[2], due to a very expansive root system that can give rise to new shoots from adventitious root buds. Canada thistle causes negative effects following direct competition for growth factors like water, light and nutrients. There are yield losses, yield problems as well as quality reduction of crop[3]. Infestation with *C. arvense* under organic farming conditions is an increasing problem in Germany and most European countries. The spread of *C. arvense* is favored by low crop competition, a high proportion of cereals and spring crops in the rotation[4] are either limited or missing autumn tillage[5,6]. Perennial weeds are very difficult to control by crop competitiveness. In order to be effective, most control options have to take place in the non-cropping period[7].

The aim of the investigation presented here was the development of a strategy for sustainable control of *C. arvense* in organic crop production. The applied strategies were targeted on the depletion of assimilate reserves in the root system by a repeated disruption of the vegetative growth of *C. arvense* by autumn tillage or cut of forage crop in combination with competition for light between crop and thistles.

Materials and Methods

From 2002 to 2004, a one-factorial field experiment (strip-plot design) was established after winter rye harvest in an area heavily infested with *C. arvense*. The trial site was located at the organic research farm 'Wiesengut' in North-Rhine Westphalia, Germany (50°48′N, 7°17′E). The experiment consisted of three strategies with different treatments, each one with four replicates (plot size 10 m × 23 m). In strategy (i) repeated stubble tillage was followed by subsequent cultivation of two forage crops.

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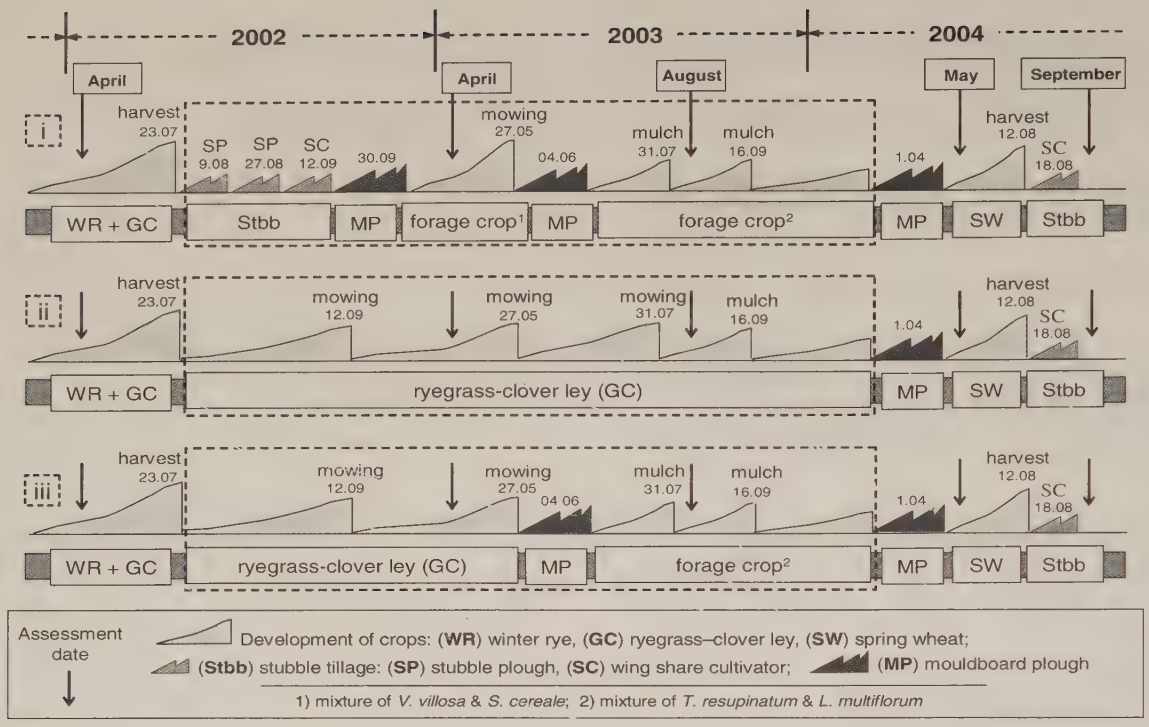

Figure 1. Three strategies for controlling *C. arvense*: variation of crop rotation and soil tillage measures, 2002–2004.

Stubble cultivation (repeated three times during August and September 2002) was carried out using a stubble plough (shallow ploughing, twice) and a wing share cultivator (once) (Fig. 1). In order to stimulate adventitious buds and to cut the emerging shoots of *C. arvense* the tillage depth was successively increased (6, 12 and 15 cm soil depth, respectively). At the time of tillage, the emerged thistle shoots had four to five leaves. According to the study of Dock Gustavsson[8] most severe depletion of assimilate reserves in the root system can be achieved with control measures at this growth stage. The interval between stubble tillage passes was 2–3 weeks. After seedbed preparation (mouldboard plough at 30-cm soil depth followed by rotary harrow combined with drilling machine), a mixture of *Vicia villosa* (L.) and *Secale cereale* (L.) (50/80 kg ha^{-1}) was sown. The forage mixture was mowed in May 2003 and then inverted by deep ploughing (30-cm soil depth). In June, another forage crop (*Trifolium resupinatum* L. mixed with *Lolium multiflorum* Lam.: 15 and 20 kg ha^{-1} respectively) was sown and mulched in July and September 2003 (Fig. 1). Strategies (ii) and (iii) were both based on ryegrass–clover ley (*Trifolium pratense* L. and *L. multiflorum*: 35 kg ha^{-1} standard mixture consisting of 29% clover and 71% ryegrass) established as underseeds in winter rye in spring 2002. In strategy (ii) the ryegrass–clover ley was maintained over the whole experiment and was regularly cut (mowed three times and then mulched). The plant material was either removed after crop mowing or was left on the field after mulching. The ryegrass–clover ley of strategy (iii) was mowed twice (September 2002 and May 2003), then ploughed (30-cm soil depth) and cultivated as in strategy (i). In March 2004, in all treatments after shallow cultivation (wing share cultivator, 10-cm soil depth), deep ploughing (30-cm soil depth) and seedbed preparation, spring wheat (cv. *Combi*, 400 seeds per m^2 at 11-cm row distance) was sown.

The following parameters were assessed: plant density, ground cover and size (rosette radius) of *C. arvense*, crop ground cover and height. Density and size of *C. arvense* shoots were determined before establishing the treatments in April 2002 on the entire trial area (23 m × 120 m) and at different times during the following years (April 2003, August 2003, May 2004 and September 2004) on four fixed standardized subplots of 3 m × 3 m size in each plot.

C. arvense density (shoots per m^2) was determined by counting the number of shoots. Size was determined by measuring of the rosette radius of shoots and classified in three groups: up to 5 cm, 5–10 cm and more than 10 cm. The rosette size of *C. arvense* shoots was used as an indicator of regrowth capacity of thistle to regenerate after treatments. Ground cover of thistles and crop were estimated during the vegetation period (all 7–10 days) by visual evaluation of covered ground by *C. arvense* (in five subplots at 1 m^2 per plot) and crop (on entire plot), respectively. Height growth of clover (cm) was determined by measuring the crop length of 10 plants in each of four subplots per plot.

The statistical analysis of data was carried out with the 'Statistical Analysis System'[9]. Parameter means were compared by multiple *post hoc* Tukey test ($\alpha = 0.05$).

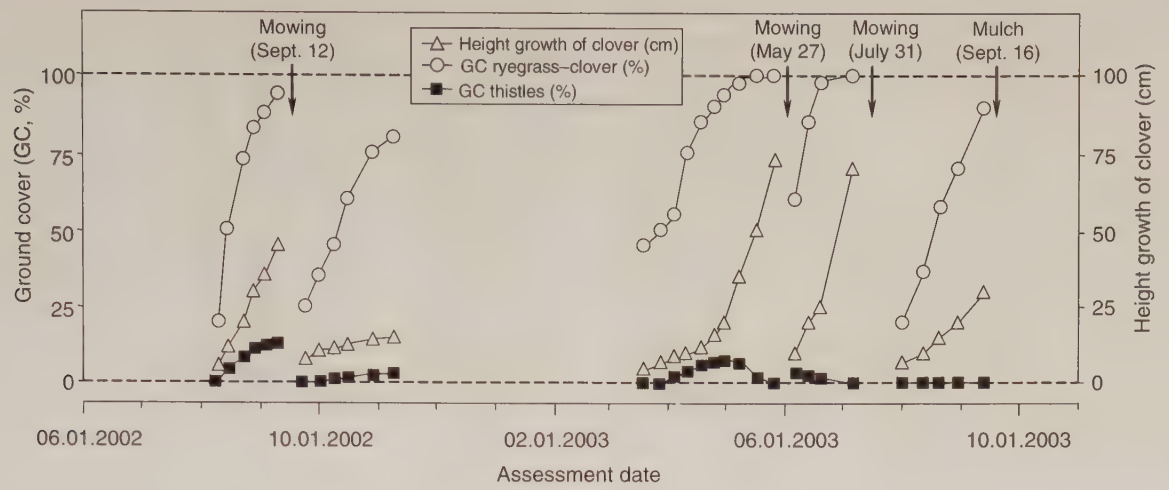

Figure 2. Development of ryegrass–clover (height growth of clover), ground cover of ryegrass–clover and thistles, respectively, during the vegetation 2002–2003 (compare Fig. 1, strategy ii).

Results and Discussion

Development of crops and thistles

Forage crops (*V. villosa* and *S. cereale*) (strategy i). Crop plants emerged about 10 days after sowing and developed very well until winter. Thistle shoots appeared sporadically. At the end of the winter crop damage was assessed as being caused by snails. During the middle of April, this crop damage was compensated by an increase of the biomass of fast developing plants (ground cover 60%), that shaded the emerged thistles (ground cover 10%) substantially. At the beginning of May, crop mixture covered ground and thistle shoots up to 100%.

Ryegrass–clover ley (strategies ii and iii). In September 2002, before the first mowing had been done, clover plants 40–45 cm high covered the ground almost completely (degree of cover: 90%, Fig. 2). At this assessment time many vigorous thistle shoots were identified, overgrowing the clover stand especially in several patches and hence, remaining unaffected by crop competition. Three weeks after the ryegrass–clover mowing the first thistle shoots developed either from the buds, on the roots or on the cut stems. The biggest part of such emerged thistles was covered by the already fast developed clover plants.

At the beginning of April 2003, ryegrass–clover ley covered the ground at about 50%, at the same time the first thistles appeared. Until mid April ground cover of the crop (height of clover stand: 50 cm) increased up to 100% (Fig. 2), and almost all *C. arvense* shoots were shaded by the crop. Only a few thistles in several patches grew undisturbed. Immediately before the cut on May 2003, the ryegrass–clover stand (75 cm height) covered the thistles completely. A lot of thistle shoots within the clover stand were very weak. The leaves of these shoots had a pale, bright yellow color. After the third cut (end of July) ryegrass–clover increased their height growth slowly due to the drought at that time.

Forage crops (*T. resupinatum* and *L. multiflorum*) (strategies i and iii). The drought period in June 2003 caused a low emergence of the forage crops. Instead, annual weeds, such as *Polygonum* spp. and *Sinapsis arvensis* (L.) established themselves very successfully despite the lack of moisture. Thus, weeds actually simulated the crop stand in our experiment. At the beginning of July, annual weeds covered the ground up to 30% and at the end of the month by up to 100% (weed height 45–50 cm). All emerged thistle shoots were completely shaded. After mulching (end of July) no further assessments were done due to drought stress resulting in poor plant growth.

Efficacy of control measures on thistle density

The distribution of *C. arvense* was extremely heterogeneous (0–60 shoots per m^2). During the first assessment in April 2002, a density of 20–40 shoots per m^2 was determined in several patches. On average, the mean number of thistles in the fixed standardized subplots was 10 shoots per m^2. This initial thistle density was the basis for the efficacy determination of all control measures. Repeated stubble tillage with subsequent forage crop cultivation (mixture of *V. villosa* and *S. cereale*) as a winter catch crop (strategy i) resulted in a decline of shoot density of *C. arvense* by about 73% (assessed after 9 months in April 2003, Fig. 3). In contrast, a patchy ryegrass–clover stand with low shading ability and mowed only once in autumn (strategies ii and iii) reduced shoot density less effectively (efficacy 40%).

Regrowth capacity (based on the size of *C. arvense* rosettes) after repeated stubble tillage was also considerably lower than after mowing of a ryegrass–clover ley. Compared to strategies (ii) and (iii), repeated stubble tillage combined with forage cropping resulted in a lower percentage of bigger-sized thistles in April 2003 (Fig. 4). These lasting effects of stubble tillage compared with

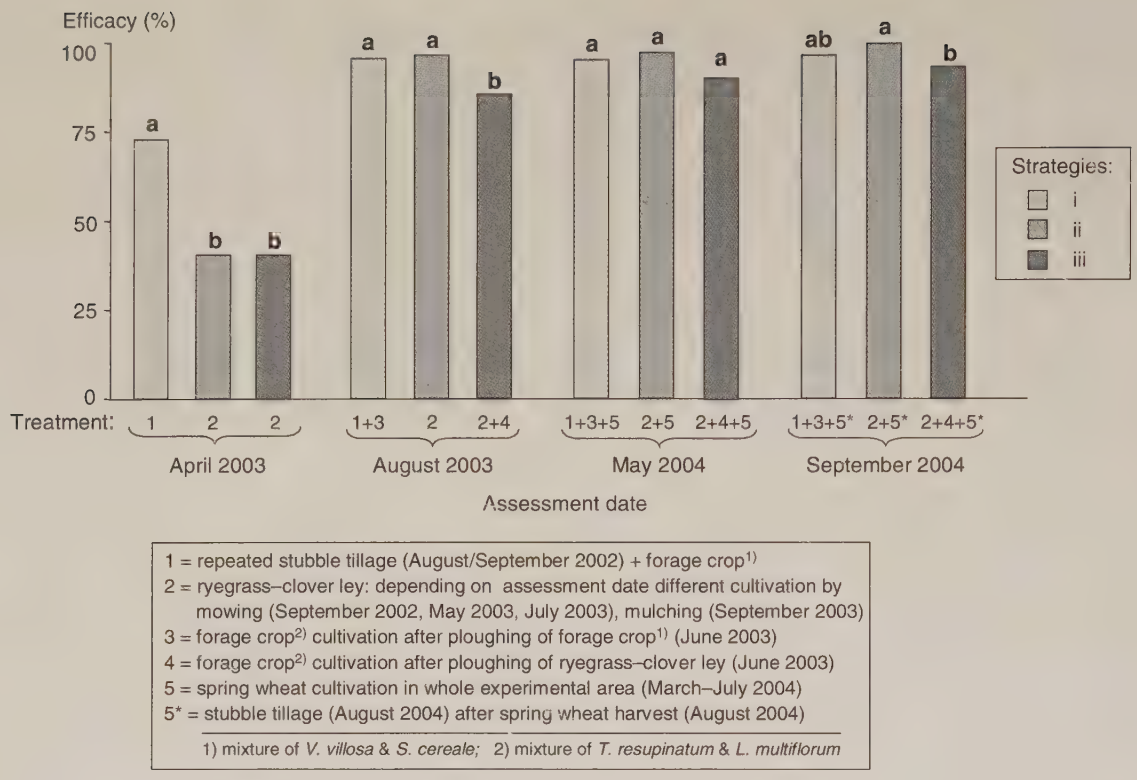
Efficacy (%)
100
75
50
25
0
a
b
b
a
a
b
a
a
a
ab
a
b
Strategies:
i
ii
iii
Treatment: 1 2 2 1+3 2 2+4 1+3+5 2+5 2+4+5 1+3+5* 2+5* 2+4+5*
April 2003
August 2003
May 2004
September 2004
Assessment date
1 = repeated stubble tillage (August/September 2002) + forage crop1)
2 = ryegrass–clover ley: depending on assessment date different cultivation by mowing (September 2002, May 2003, July 2003), mulching (September 2003)
3 = forage crop2) cultivation after ploughing of forage crop1) (June 2003)
4 = forage crop2) cultivation after ploughing of ryegrass–clover ley (June 2003)
5 = spring wheat cultivation in whole experimental area (March–July 2004)
5* = stubble tillage (August 2004) after spring wheat harvest (August 2004)
1) mixture of V. villosa & S. cereale; 2) mixture of T. resupinatum & L. multiflorum

Figure 3. Efficacy of control measures: effect of repeated stubble tillage with subsequent forage crop cultivation (strategy i), repeated mowing of a ryegrass–clover ley (strategy ii) and forage crop cultivation following a ryegrass–clover ley (strategy iii) on *C. arvense* density (100% = 10 shoots per m^2 = mean initial density of *C. arvense* in April 2002). Different letters within the column group indicate significant differences (Tukey test, $\alpha = 0.05$).

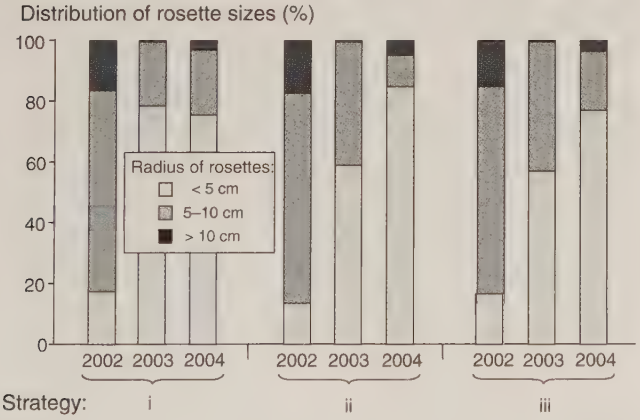

Figure 4. Effect of repeated stubble tillage combined with subsequent forage crop cultivation (strategy i), repeated mowing of a ryegrass–clover ley (strategy ii) and forage crop cultivation following a ryegrass–clover (strategy iii) on the rosette size of *C. arvense* (assessment: April 2002, April 2003 and May 2004). Differences of rosettes sizes among different strategies at the same assessment date are not significant (Tukey test, $\alpha = 0.05$).

forage crop cultivation can be explained by the efficient continuous depletion of assimilates bound in the *C. arvense* root system, resulting in a decreased regrowth capacity of *C. arvense* by stimulating the emergence of new shoots together with repeated cutting of *C. arvense* shoots[10,11]. At the following assessment date (May 2004) a similar distribution of *C. arvense* rosette sizes in all strategies was determined.

As shown in Fig. 3, subsequent forage crop cultivation after repeated stubble tillage (strategy i) was just as effective as a ryegrass–clover ley mowed three times (September 2002, May 2003 and July 2003, strategy ii) in reducing thistle density in August 2003. The efficacy of these two treatments was high at 96%. The efficacy of forage crop cultivation (mixture of *T. resupinatum* and *L. multiflorum*) after ploughing of ryegrass–clover ley in June 2003 (strategy iii) was also high (86%); however, significantly lower than that of the other two treatments. This was due to increased thistle density as a result of damage to the apical dominance of shoots during ploughing. The initially low shading ability of the forage crop was obviously not sufficient to stop the growth of emerging *C. arvense* shoots. Other studies have demonstrated the importance of a dense competitive crop stand for successful thistle suppression[12,13].

In May 2004, 22 months after the beginning of the experiment, long-term effects of strategy (i) (stubble tillage combined with competitive forage crops) and three times mowing and one mulching ryegrass–clover ley (strategy ii) also became apparent, as the shoot density of *C. arvense* decreased (efficacy 95–97%). The efficacy of forage crop cultivation following twice-mowed ryegrass–clover ley

(89%, strategy iii) was not significantly different from both other treatments (Fig. 3). Combinations of competition for light, water and nutrients among crop and thistles with repeated removal of *C. arvense* shoots obviously contributed to fast depletion of assimilate reserves in the root system of thistles in all tested strategies. These results confirm other studies that have demonstrated a higher crop (ryegrass–clover) competition in combination with repeated mowing significantly decreased the shoot density of *C. arvense*[3,14]. Repeated mowing of forage such as alfalfa or legume–grass mixtures can severely reduce thistle density. Hodgson[2] found that after 4 years of alfalfa, mowing alfalfa fields twice a year reduced *C. arvense* to 1% of its initial value. The frequency of defoliation corresponds with the degree of reduction of root assimilates. This relation has also been demonstrated in studies where topping of *C. arvense* shoots was followed by repeated grazing[15].

In our experiment, the regenerative capacity of thistles was considerably lower than that of clover when ryegrass–clover ley was mowed and/or mulched. The same response of *C. arvense* was observed by Hodgson[16] after alfalfa was cut. According to Dock Gustavsson[17], the slow regeneration of thistles after the mowing of ryegrass–clover ley can be one of the most important reasons for thistle density reduction from year to year.

The timing of cultivation may be important for reducing *C. arvense*. Root carbohydrate reserves can vary with the season[18,19]. The lowest amount of assimilate reserves in the root system is considered to be found in early June, when flowering of *C. arvense* starts[2,20–22]. Development of reproductive parts on the thistle plant results in high consumption of root assimilate reserves, placing the plant into a weakened state[23]. Thus, during May/June thistle plants are considered equally susceptible to the different types of disturbance, i.e. deep ploughing (strategies i and iii) or mowing/mulching (strategy ii). Both root system and aerial shoots of undisturbed plants grow rapidly in a period immediately following this weak stage[10,24], combined with efficient accumulation of carbohydrate reserves.

Dry weather conditions in summer 2003 might have caused a further reduction of *C. arvense* in the ryegrass–clover stand. Drought stress has been shown to increase the efficacy of mechanical control of *C. arvense*[25]. When shoots are removed, root buds are stimulated to produce new shoots that might otherwise be suppressed, especially under water deficiency growing conditions[26]. One can assume, that particularly under water stress, repeatedly disturbed and seriously weakened thistles were no longer able to emerge in our experiment. This fact could explain the strong reduction of *C. arvense* shoot density in summer 2003 as well as in spring 2004.

Final assessment in September 2004, 26 months after the beginning of the experiment resulted in efficacies of 96 and 99% in strategies (i) and (ii), respectively, whereas the efficacy of strategy (iii) (93%) was significantly lower than that of strategy (ii) (Fig. 3). These results indicated that control measures provided nearly complete thistle control throughout the duration of the experiment.

Conclusions

Our results suggest that the most effective medium-term (9 months) control of *C. arvense* in heavily infested areas is given by repeated stubble cultivation combined with increasing tillage depth and cultivation of a subsequent competitive crop. This method can mainly be recommended for vegetable growers or farmers without livestock, who cannot integrate perennial forage crops in their rotation. Efficient sustainable control of *C. arvense* can also be achieved by using a ryegrass–clover ley that is repeatedly mowed. Three mowings per season provide a better thistle control than two mowings. Mowing should be performed before the thistle shoots grow atop the crop stand and will get the full sunlight. High ground cover of ryegrass–clover ley (95–100%) is compulsory to minimize light access for residual emerging *C. arvense* shoots, and to limit the plants' replenishment with assimilates. This strategy can be recommended especially for forage production and production systems that require flexible crop rotations. Due to higher costs and lower efficacy, the strategy of forage crop cultivation following ploughing of ryegrass–clover ley in the phase of high susceptibility of *C. arvense* (May/June) cannot be recommended.

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Tanniferous forage plants: Agronomic performance, palatability and efficacy against parasitic nematodes in sheep

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Abstract

Tanniferous forage plants can have beneficial effects on ruminant productivity and health (improved protein supply, bloat safety and antiparasitic properties). However, condensed tannins can also lower palatability, voluntary feed intake and digestibility. The aim of our interdisciplinary project was to generate basic knowledge on plant management, feed palatability and the antiparasitic properties of tanniferous forage plants for their practical application in agronomy, focusing on their usefulness in controlling gastrointestinal nematodes in organic farming. We found that *Onobrychis viciifolia* (sainfoin), *Lotus corniculatus* (birdsfoot trefoil) and *Cichorium intybus* (chicory) were suitable for cultivation under the given temperate climatic conditions, whereas *Lotus pedunculatus* (big trefoil) was soon outcompeted by unsown species. Growing the tanniferous plant species in a mixture with *Festuca pratensis* (meadow fescue) rather than in a monoculture had the advantage of increasing total dry matter (DM) yield (especially in the case of tanniferous legumes) and of reducing the DM proportions of unsown species. However, due to dilution by non-tanniferous *F. pratensis*, the tannin concentrations of mixtures were clearly lower and the seasonal fluctuations in tannin concentrations greater than that of monocultures. Across species, tannin concentrations were highest for *O. viciifolia*, followed by *L. corniculatus* and very low for *C. intybus*. Palatability of all tanniferous forages was comparable to that of a ryegrass/clover mixture when fed as dried forage and, when offered as silage, palatability of *O. viciifolia* was clearly superior to that of the respective ryegrass/clover control. Administration of dried or ensiled *O. viciifolia* reduced parasite egg counts in feces of lambs co-infected with the gastrointestinal nematode species *Haemonchus contortus* and *Cooperia curticei*. We conclude that *O. viciifolia* is the most promising among the tested tanniferous forage plant species due to its suitability for cultivation, its high tannin concentration, its high palatability and its antiparasitic activity even in dried or ensiled form.

Key words: condensed tannins, proanthocyanidins, forage cultivation, yield, silage, palatability, gastrointestinal nematodes, parasite control, sheep

Introduction

Recent experiments in agronomy and parasitology suggest that moderate dietary concentrations of condensed tannins can affect the health and performance of sheep and other small ruminants beneficially[1–5]. For example, condensed tannins were found to increase life weight gain, fecundity and wool production in sheep[6,7]. With regard to animal health, condensed tannins are known to diminish the risk of bloat, lower fecal worm egg excretion and reduce worm burdens of parasitized ruminants[3,5]. However, high concentrations of condensed tannins can have a negative

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impact on ruminants. They can lower palatability and digestibility[5,8] and, in extreme cases, they can lead to mucosal lesions[9].

In an interdisciplinary project involving research on plant cultivation, animal nutrition and parasitology, we addressed key questions concerning the implementation of tanniferous forage plants as an alternative control strategy against gastrointestinal nematodes in animal husbandry: Which tanniferous species and cultivars (cv.) perform well with regard to agronomic properties such as yield, persistence and competitive ability? What are their concentrations of condensed tannins and what are the most important drivers of fluctuations in tannin concentrations under field conditions? How palatable are different tanniferous forage plant species in comparison to a ryegrass/clover mixture? How effective is the most promising plant species against gastrointestinal nematodes in sheep? Can tanniferous forages be conserved without losing their desirable anthelmintic properties?

Plant Sciences and Forage Cultivation

The expressions 'condensed tannins' or synonymously 'proanthocyanidins' summarize a large and chemically diverse group of phenolic polymers with the ability to bind proteins and other macromolecules. Apart from their strong affinity for proteins, condensed tannins can form complexes with metal ions and have radical scavenging properties[10]. The structure of condensed tannins consists of a linkage of a series of monomers based on flavan-3-ol nuclei or derivatives thereof[11]. Variations in the structure of condensed tannins (and supposedly of their bioactivity) can occur through differences in the number of monomers, the positions between which these monomers are interlinked, the oxygenation pattern of the monomers or the stereochemistry of the polymer[11,12]. Condensed tannins exist as water-soluble oligomers and as insoluble polymers[10]. Tanniferous plants usually contain mixtures of differently structured tannins rather than one specific type of molecule[11,13]. The quantity and structural composition of tannins vary between different tissues and can change during plant development[13,14]. Condensed tannins occur predominantly in woody plants but can also be found in some herbaceous plant species, for example in representatives of the Rosaceae and Fabaceae families[11]. Within plants, condensed tannins are concentrated in cell vacuoles[12] and usually occur in higher concentrations in leaves and reproductive organs than in stems and roots[14].

The bioactivity of condensed tannins is thought to be a function of tannin concentrations defined as the ratio between consumed tannin and consumed protein or feed[11] rather than of the absolute amount of consumed tannin. As a rule of thumb it has repeatedly been suggested that tannin concentrations below $50\,g\,kg^{-1}$ DM produce positive effects in ruminants, while concentrations in excess of $50\,g\,kg^{-1}$ DM affect the animal negatively[1,4]. Today's experimental evidence relativizes this rule to the extent that tannins from different sources may vary in their 'potency'[5] and that it is likely that different thresholds need to be defined for different tannins and, thus, different forage plant species.

Genotypic and phenotypic variation of type and quantity of secondary metabolites have often been studied within the paradigm that their primary role is plant defensive and their effect on consumers detrimental. The accumulated experimental evidence for and against the so-called plant defense theory[15–18] is equivocal[19,20] and its usefulness for the practical application in agronomy disputable[14]. Previous studies of seasonal fluctuations of tannin concentrations in forage plants yielded conflicting results[14,21–24] and mechanisms driving seasonal and developmental dynamics of tannin concentrations under field conditions are not yet well understood. Based on an experiment with potted *Onobrychis viciifolia* and *Lotus corniculatus*, it has been suggested that fluctuations in condensed tannin concentrations in harvestable aboveground biomass are functions of biomass proportions between tannin-rich leaves and tannin-poor stems in pure stands, and of biomass proportions between tanniferous and non-tanniferous plant species in mixed stands[14]. At present, it is unclear to what extent these hypotheses hold true under field conditions.

For a successful implementation of a gastrointestinal nematode control strategy based on tanniferous forage plants, it is essential that the tanniferous forage crop provides a high yield, has a high competitive ability and an elevated but predictable concentration of condensed tannins. Especially under low input conditions, the agronomic performances of species mixtures have been reported to be superior to those of monocultures. In comparison to monocultures, mixtures are often characterized by higher dry matter (DM) yields[25], improved evenness of the seasonal growth patterns[26] and increased resistance against weed invasion[25]. Until now, comparative assessments of agronomic performances of promising tanniferous forage plants and concurrent investigations of tannin concentration dynamics under field conditions have been scarce.

Therefore we evaluated yield, resistance to weed invasion and tannin concentrations of 12 cultivars of four commercially available, tanniferous forage plant species which were either sown in a monoculture or in a mixture with the grass species *Festuca pratensis* in a three-year field experiment. We put special emphasis on investigating to what extent potential seasonal fluctuations of condensed tannin concentrations in the yield can be attributed to shifts in the relative DM contribution of tanniferous plants to total DM yield.

Animal Nutrition

Palatability designates the sum of all physical and chemical characteristics of a diet that evoke appetite, such as olfactory, gustatory and tactile stimuli during foraging and chewing[27]. Repeated feeding of a particular diet

enables an animal to anticipate potential nutritional and physiological postingestive feedbacks and eventually to develop a preference for or an aversion against it[28]. The perception of a diet, and subsequent feed preferences, vary among individual animals according to differences in physiology and experience[29]. Therefore, palatability and food preference are questions of physiological traits of the animal, of individual experience and of the feed quality of the forage in question in relation to the range of feeds available to the animal.

There is a wealth of evidence suggesting that condensed tannins in plants influence the voluntary feed intake, palatability and digestibility of the fodder[2,4,5]. It is thought that the importance of condensed tannins in animal nutrition lies mainly in their ability to bind proteins. For example, the astringent taste of tanniferous plants is a consequence of the binding of tannins to salivary proteins. The lower true digestibility of feed proteins, the increase of the excretion of endogenous protein in pigs[30], and the lower ruminal protein degradability combined with a lower apparent digestibility in ruminants[31] are results of the binding of tannins to feed protein and endogenous proteins. While protein precipitation in the intestine lowers amino acid availability and affects the ruminant adversely, protein precipitation and protein protection from microbial degradation in the rumen can be desirable and beneficial to the animal[32]. The binding of condensed tannins to protein in the rumen (pH 6–7) lowers ammonia production and reduces the metabolic strain of the liver (2). Furthermore, it enhances the protein flow towards the small intestine and, provided the tannin–protein complexes dissociate in the more acid medium of the abomasum ($pH < 3$), raises the animal's supply of essential amino acids[5,33]. An improved protein supply of the ruminant is one of the possible pathways leading to an increased tolerance of ruminants to gastrointestinal parasite infections[3,34]. In addition to the likely impact of condensed tannins on nitrogen metabolism, tannins may also affect the mineral supply of the animal[35,36]. For the practical application of tanniferous forages in livestock production, e.g. as an alternative nematode control strategy, administration of forage plants in a conserved form (either as dried or ensiled forage) is of great interest. In previous experiments, condensed tannins were reported to depress proteolysis thereby reducing the loss of forage protein during the ensiling process[37]. Furthermore, it was observed that ensiling reduced tannin concentrations of sorghum[38]. Up to now, little is known about the effect of ensiling on the palatability of tanniferous forage plants.

Feeding trials provide an ideal means of obtaining a brief and summary-like answer to the complex question of whether or not a certain (tanniferous) forage plant species is suitable for its consumer, and allow an assessment of voluntary feed intake and possible side effects of the feed. In this study, we aimed to identify the most promising tannin-containing plant species and conservation method in terms of the wethers' acceptance and, thus, palatability of dried or ensiled *O. viciifolia*, *L. corniculatus* and *Cichorium intybus* in relation to a dried or ensiled non-tannin-containing ryegrass/clover mixture, respectively.

Parasitology

Infections with gastrointestinal nematodes represent a major constraint on the profitability of sheep, goat and cattle production. This is particularly pronounced in low-input farming where animals are grazing on pastures, in contrast to intensive production systems in which access to pasture is limited or even absent[39]. The organic farmer is confronted with the problem of (i) reducing the infection pressure to an acceptable level and (ii) having largely to resign himself to the use of conventional anthelmintic drugs in order to keep within the organic guidelines. As complementary approaches to control gastrointestinal parasitism of small ruminants, such as the exploitation of the genetic resistance of livestock[40], biological control of the free-living larval stages in the feces by means of nematophagous fungi[41,42], manipulation of grazing management[43] and dietary supplementation with protein[44], were each only partially effective, the control of endoparasites remains largely based on the application of synthetic anthelmintic drugs. The development of gastrointestinal parasite populations resistant against most of the currently available anthelmintics further highlights the need for alternative parasite control strategies[45].

Recent experiments with tanniferous forages administered to sheep and goats infected with gastrointestinal nematodes yielded promising results[3]. Tanniferous forages that were grazed, or freshly administered, to naturally or artificially infected animals often resulted in a decreased fecal egg count (i.e. the number of worm eggs per gram feces of the host), which was sometimes accompanied by a reduction of worm burden (i.e. the number of adult worms) or reductions in worm fecundity. The potential of condensed tannins as an antiparasitic agent has been substantiated by various *in vitro* and *in vivo* experiments: condensed tannins were found to reduce the parasites' motility, possibly by binding to surface proteins, to exert a toxic effect on parasite eggs, larvae or adult worms and to hinder larval development[3,46]. Alternatively or complementary to these 'direct effects', condensed tannins can exert indirect effects. For example, they may help to improve the host's immune response to parasitism (i.e. resistance) by enhancing the ruminant's supply of proteins and essential amino acids[3].

Administering tanniferous forages to parasitized ruminants in a conserved form, either as hay or silage, could potentially enhance the practicability and efficacy of the treatment. However, experiments with conserved forages remain few. Therefore, we tested the feeding of *O. viciifolia* hay and silage, respectively, to lambs co-infected with *Haemonchus contortus* and *Cooperia curticei* in comparison to non-tanniferous control feeds[47].

Methods

Agronomic performance of tanniferous forage plants

We assessed the yield, the competitive ability and the tannin concentration in the yield of 12 cultivars of four tanniferous plant species sown in monoculture or in a mixture with a non-tanniferous grass species. Plant performances were observed from sowing in spring 2004 until the last harvest in May 2006. The experiment included *O. viciifolia* (sainfoin, fam. Fabaceae: ecotype Alvaschein, commercial seed, cv. Visnovsky), *Lotus pedunculatus* (big trefoil, fam. Fabaceae: cv. Grasslands Maku, cv. Barsilvi, cv. Grasslands Sunrise), *L. corniculatus* (birdsfoot trefoil, fam. Fabaceae: cv. Odenwälder, cv. Lotar, cv. Oberhaunstädter), *Cichorium intybus* (chicory, fam. Asteraceae: cv. Grasslands Puna, cv. Forage Feast, cv. INIA Lacerta). For the mixtures, we selected *F. pratensis* (meadow fescue, fam. Poaceae: cv. Preval), a grass suitable for low-input farming with a high nutritive quality but with limited potential as a competitor.

The field experiment was done at Agroscope Reckenholz-Tänikon, Research Station ART, in Zurich, Switzerland (47°26′N, 8°30′E). The block experiment (three blocks) was sown with 'plant species' as the main plot factor, 'cultivar' as the subplot factor and 'purely sown versus mixture' as the sub-subplot factor[48]. Within each main plot (species), the cultivars were assigned randomly to pairs of sub-subplots with an area of 9 m^2 (1.5 m × 6 m) each. On one of these plots the tanniferous cultivar was sown in monoculture; on its neighboring plot, it was sown in a mixture with the grass *F. pratensis*. To complete the design, each block contained two grass monocultures of 9 m^2 size (i.e. *F. pratensis* cv. Preval). Sowing densities of monocultures of *O. viciifolia*, *L. pedunculatus*, *L. corniculatus*, *C. intybus* and *F. pratensis* corresponded to 180, 18, 18, 4 and 25 kg ha^{-1} of germinable seed, respectively. For the mixtures, we replaced 40% of the respective tanniferous plant species seed by 40% of *F. pratensis* seed (i.e. 25 kg ha^{-1} × 40% = 10 kg ha^{-1}). Per block, one grass sward and all plots containing legumes (i.e. plants of the family Fabaceae with the ability of N_2-fixation by means of symbiotic rhizobia) were fertilized with only 25 kg N ha^{-1} after each harvest. The remaining grass monocultures and the chicory plots were fertilized with 50 kg N ha^{-1} after each harvest.

Swards were harvested twice in the year of sowing (i.e. 2004), four times in 2005 and a last time in spring 2006. On each of these occasions, three bands of 10 cm width were cut across every sward at 7 cm above ground level for an assessment of the botanical composition of the harvest and a quantification of its tannin concentration. A random subsample (one-third) of that plant material was immediately put on ice for transportation and dried at 60°C for 48 h as soon as possible, ground to pass through a 0.75 mm sieve, and stored in the dark at room temperature before it was analyzed for condensed tannins using a butanol–HCl-assay with a *L. pedunculatus* standard[49]. The remaining two-thirds of the plant material were separated into 'sown tanniferous species', 'sown *F. pratensis*' and 'unsown species'. The separated plant fractions were dried at 100°C for 24 h to calculate their relative contributions to the total DM yield. After collecting the botanical samples, swards were harvested by machine, 7 cm above ground level and the total DM yield of each sward was determined.

Feed palatability

In two consecutive but independent experiments of 20 days' duration each, the palatability for wethers of three tanniferous forage plant species (i.e. *O. viciifolia*, *L. corniculatus* and *C. intybus*) was tested in comparison to a control feed consisting of a ryegrass/clover mixture. In a first experiment, feeds were offered as dried forages; in a second experiment they were offered as silages.

O. viciifolia cv. Visnovsky, *L. corniculatus* cv. Oberhaunstädter, *C. intybus* cv. Grasslands Puna and a ryegrass/white clover/red clover mixture were grown in 2003 at Agroscope Liebefeld-Posieux, Research Station ALP, Posieux (46°46′N, 7°06′E), Switzerland. The tanniferous forages were topped once at the beginning of July, harvested in August and ensiled in 700-liter containers. Second harvests were taken at the end of September (*C. intybus*) or in mid October (*O. viciifolia, L. corniculatus*), respectively, and dehydrated at 30°C to a water content below 10% using a special drying system (Physitech, Wabern, Switzerland) that minimized the loss of tannin-rich plant leaf material. The non-tanniferous control mixture was taken from the fourth cut at the end of September from a ley and was likewise dried or ensiled. The tannin concentrations of the forages were analyzed using a butanol–HCl-assay with a *L. pedunculatus* standard[49].

The experiment involved three groups of adult Oxford wethers ($n = 6$) corresponding to the three tanniferous forage plant species. On average, wethers were 4.1 ± 1.8 years old and had a weight of 87.6 ± 7.2 kg; they were individually housed in pens. Wethers were offered a choice between the respective tanniferous forage and the control feed, which were presented simultaneously in two separate boxes. During the first 10 days of each experiment, the diets contained 110% of the maintenance energy requirement and were given in equal portions twice a day. The maintenance energy requirement [ME_m in MJ; equation (1)] was calculated as a function of the life weight (LW) of each animal and expressed as metabolizable energy[50]:

$$ME_m = 0.38 \times LW^{0.75} \quad (1)$$

During the second 10 days, the sheep received half of the experimental diets (55% ME_m) at 07:00 h and additionally low-quality hay (100% ME_m) at 16:00 h. Individual forage-specific feed intake was measured twice a day: once after a short evaluation period t ($t = 7.5$ min for ensiled forage and $t = 15$ min for dried forage) and once in the afternoon at

Table 1. Total yield, DM proportion of sown species, DM proportion of tanniferous species and tannin concentration of total yield harvested in the year 2005 (mean ± SE; $n = 3$, swards were cut four times in 2005). All cultivars were sown in 2004 either as pure stands or in mixture with *F. pratensis*. CT, condensed tannin.

	Total yield ($t\,ha^{-1}\,yr^{-1}$ DM)		Sown species (% of total yield)		Tanniferous species (% of total yield)		Tannin conc. of yield ($g\,CT\,kg^{-1}$ DM)	
	Pure	Mixture	Pure	Mixture	Pure	Mixture	Pure	Mixture
O. viciifolia[1]								
Alvaschein	11.0 ± 0.3	16.4 ± 1.1	46 ± 8	90 ± 2	46 ± 8	6 ± 1	21 ± 4	4 ± 1
Commercial seed	11.1 ± 0.2	16.4 ± 1.1	38 ± 13	96 ± 1	38 ± 13	6 ± 3	17 ± 3	4 ± 2
Visnovsky	13.0 ± 1.2	16.5 ± 1.6	76 ± 6	98 ± 1	76 ± 6	36 ± 3	24 ± 2	12 ± 1
L. pedunculatus[1]								
Maku	7.7 ± 0.3	18.1 ± 1.0	19 ± 3	88 ± 1	19 ± 3	5 ± 2	13 ± 3	4 ± 1
Barsilvi	9.0 ± 1.1	17.1 ± 0.1	2 ± 1	76 ± 1	2 ± 1	1 ± 1	4 ± 1	1 ± 1
Sunrise	8.6 ± 1.1	17.6 ± 1.0	5 ± 1	83 ± 3	5 ± 2	1 ± 1	5 ± 1	2 ± 1
L. corniculatus[1]								
Odenwälder	9.9 ± 1.0	18.0 ± 1.2	70 ± 12	95 ± 3	70 ± 12	21 ± 9	17 ± 1	6 ± 1
Lotar	11.0 ± 1.0	18.4 ± 1.1	77 ± 5	97 ± 1	77 ± 5	32 ± 9	18 ± 2	10 ± 2
Oberhaunstädter	10.0 ± 1.5	17.3 ± 1.1	77 ± 6	89 ± 4	77 ± 6	39 ± 10	15 ± 1	8 ± 1
C. intybus[2]								
Puna	12.8 ± 1.0	12.8 ± 0.6	100 ± 0	100 ± 1	100 ± 1	94 ± 2	5 ± 1	4 ± 1
Forage Feast	9.9 ± 0.5	12.6 ± 0.7	99 ± 1	98 ± 2	99 ± 1	72 ± 9	5 ± 1	3 ± 1
Lacerta	12.1 ± 1.2	12.5 ± 1.5	100 ± 0	100 ± 1	100 ± 1	87 ± 1	2 ± 1	3 ± 1
F. pratensis								
Preval[2]	13.8 ± 0.8	–	92 ± 2	–	–	–	–	–
Preval[1]	14.2 ± 1.2	–	82 ± 1	–	–	–	–	–

[1] $100\,kg\,N\,yr^{-1}$.
[2] $200\,kg\,N\,yr^{-1}$.

16:00 h. The daily palatability index [PI; equation (2)] was calculated according to the following formula[51]:

$$PI(t) = I_T(t)/I_C(t) \times 100 \quad (2)$$

where $I_T(t)$ corresponds to the intake of the tanniferous forage eaten during the first t minutes divided by the total intake of tanniferous plants until 16:00 h. Analogously, $I_C(t)$ refers to the intake of the control forage eaten during the first t minutes divided by the total intake of the control forage until 16:00 h. The palatability index assumes that forage selection and intake rates at the beginning of a meal are good criteria to determine palatability of forage. The palatability index exceeds 100% when the percentage of the daily-consumed tanniferous forage already eaten after t minutes is larger than the corresponding percentage of the control forage. The palatability of the non-tanniferous control feed is defined as 100%, and tanniferous forages for which the palatability index exceeds 100% are more palatable than the control feed.

Antiparasitic activity of O. viciifolia *hay or silage*

The present feeding experiment aimed to assess the efficacy of dried or ensiled forage of *O. viciifolia* against gastrointestinal nematodes in sheep. Twenty-four Swiss white alpine × Swiss Black-Brown Mountain lambs (10 females and 14 males) were artificially infected with a single dose of *C. curticei* and *H. contortus* larvae. The lambs were between 2.5 and 3 months old and had a mean liveweight of 33 kg at the start of the experiment. Twenty-eight days post infection, the lambs were allocated to four comparable groups according to sex, bodyweight and fecal egg counts. For 16 days, the lambs were fed *ad libitum* with either *O. viciifolia* or a corresponding isoproteic and isoenergetic non-tanniferous control forage each as regular hay or silage, respectively. Fecal egg counts per gram dry feces were performed twice a week. Tannin concentrations of the forages were analyzed using a butanol–HCL assay with a *L. pedunculatus* standard[49].

Results and Discussion

Agronomic performance of tanniferous forage plants

O. viciifolia, *L. corniculatus* and *C. intybus* germinated and established well in 2004. In contrast, all cultivars of *L. pedunculatus* were soon outcompeted after an initially promising germination, mainly by unsown *Trifolium repens*. As a result, the DM proportions of *L. pedunculatus* were below 20% DM of the accumulated yield in 2005 (four harvests) for any of the cultivars even when they were sown as a monoculture (Table 1). Therefore, the following text will concentrate on results of *O. viciifolia*, *L. corniculatus* and *C. intybus* only.

The cultivars of *O. viciifolia*, *L. corniculatus* and *C. intybus* yielded between 9.9 and 13.0 t DM ha^{-1} yr^{-1} when sown in a monoculture (Table 1). Sowing the tanniferous plants in a mixture with *F. pratensis* increased the total yield markedly in the case of *O. viciifolia* (yields of mixtures ranged from 16.4 to 16.5 t DM ha^{-1} yr^{-1}), and even more so in *L. corniculatus* (yields of mixtures ranged from 17.3 to 18.4 t DM ha^{-1} yr^{-1}) but only slightly in *C. intybus* (yields of mixtures ranged from 12.5 and 12.8 t DM ha^{-1} yr^{-1}). In the case of *O. viciifolia* and *L. corniculatus*, yields of mixtures clearly exceeded the yields of both the respective monocultures of the tanniferous plant species as well as that of the grass monoculture. This transgressive overyielding resulted most likely from N_2-fixation[52] of the tanniferous legume species and from a spatial and temporal niche complementation with regard to growth.

For *O. viciifolia*, *L. corniculatus* and *C. intybus*, DM proportions of sown species in the yield ranged from 38 to 100% when the tanniferous cultivars were sown in a monoculture but between 89 and 100% when they were sown in a mixture with *F. pratensis* (Table 1). In other words, *F. pratensis* helped to reduce the invasion of weed and other unsown species both in terms of absolute and relative amounts of weed. However, the grass also reduced the proportion of sown tanniferous plant material in the harvest from 38–100% in monoculture to 6–94% in mixtures and, as a consequence, tannin concentrations in the harvest of mixtures were diluted accordingly (Table 1). Between species, differences in tannin concentrations at the yield level (Table 1) were much smaller than might have been expected from tannin concentrations of the tanniferous species alone (Fig. 1). While the yield of species with high tannin concentrations (i.e. *O. viciifolia* and *L. pedunculatus*) was at times heavily diluted by non-tanniferous plant material, this dilution was less severe in *L. corniculatus*, which has intermediate tannin concentrations and almost non-existent in the case of *C. intybus*, which has very low tannin concentrations.

Cultivar Visnovsky was clearly the most promising among the tested *O. viciifolia* cultivars. Visnovsky had the highest yield (when sown as a monoculture: 13.0; when sown as a mixture: 16.5 t ha^{-1} yr^{-1} DM) and the highest DM proportions of the sown plant species (monoculture: 76, mixture: 98% DM), the highest DM proportion of tanniferous plant material in the yield (monoculture: 76, mixture: 36% DM) and therefore also the highest tannin concentrations (monoculture: 24, mixture: 12 g kg^{-1} DM). For *L. corniculatus*, cultivar Lotar performed slightly better than cv. Oberhaunstädter and cv. Odenwälder. Lotar achieved a yield of 11.0 t ha^{-1} yr^{-1} in monoculture and 18.4 t ha^{-1} yr^{-1} in a mixture with *F. pratensis*. The proportion of tanniferous plants was 77% in monoculture and 32% when sown in a mixture and the tannin concentration of the yield (monoculture: 18, mixture: 10 g kg^{-1} DM) was only slightly lower than in *O. viciifolia*. Among the tested cultivars of *C. intybus*, the cultivar Puna

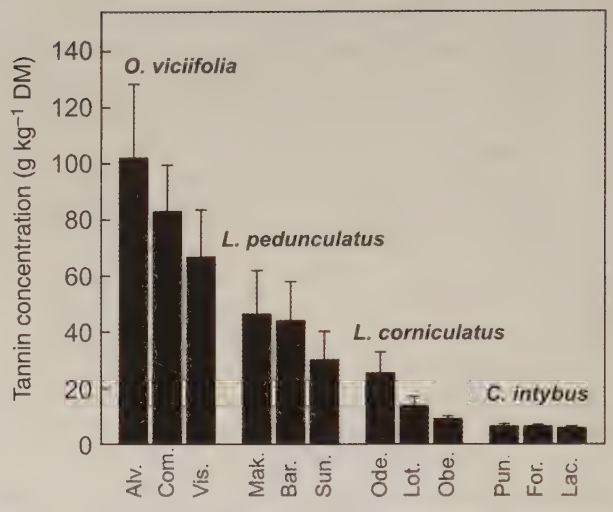

Figure 1. Tannin concentrations of harvestable aboveground biomass (>7 cm; mean ± SE; $n = 3$) of 12 field-grown tanniferous cultivars: *O. viciifolia*: ecotype Alvaschein (Alv.), commercial seed (Com.), cv. Visnovsky (Vis.). *L. pedunculatus*: cv. Grasslands Maku (Mak.), cv. Barsilvi (Bar.), cv. Grasslands Sunrise (Sun.). *L. corniculatus*: cv. Odenwälder (Ode.), cv. Lotar (Lot.), cv. Oberhaunstädter (Obe.). *C. intybus*: cv. Grasslands Puna (Pun.), cv. Forage Feast (For.), cv. INIA Lacerta (Lac.). All cultivars were collected on 8 May 2006.

clearly performed best. The other cultivars produced a large amount of stems, especially in the second year, adding to the DM yield and the DM yield proportions but supposedly reducing the forage quality.

Figure 2 displays the DM proportion of tanniferous plant material in each harvest and the corresponding tannin concentration for the most promising species and cultivars in this study (i.e. *O. viciifolia* cv. Visnovsky and *L. corniculatus* cv. Lotar). In both purely sown and mixed stands of *O. viciifolia* or *L. corniculatus*, respectively, fluctuations of DM proportions between tanniferous plants and non-tanniferous plant species were considerable. For example, in monocultures of *O. viciifolia* cv. Visnovsky, the proportion of tanniferous plants was 80% in August 2004, decreased to 55% DM in October of the same year but recovered to almost 100% DM in July of the following year. Shifts in the relative contribution of tanniferous plant material to total yield were reflected in the seasonal dynamics of tannin concentrations in the harvest. Therefore, we conclude that shifts in DM proportions and the competitive abilities of the tanniferous plant species are major drivers of seasonal fluctuations of tannin concentrations in the harvest.

Feed palatability

O. viciifolia had the highest concentration of condensed tannins, followed by *L. corniculatus*, while the tannin concentration of *C. intybus* was low. For all the investigated plant species, tannin concentrations (g kg^{-1} DM) were higher in silage (*O. viciifolia*: 100; *L. corniculatus*: 41;

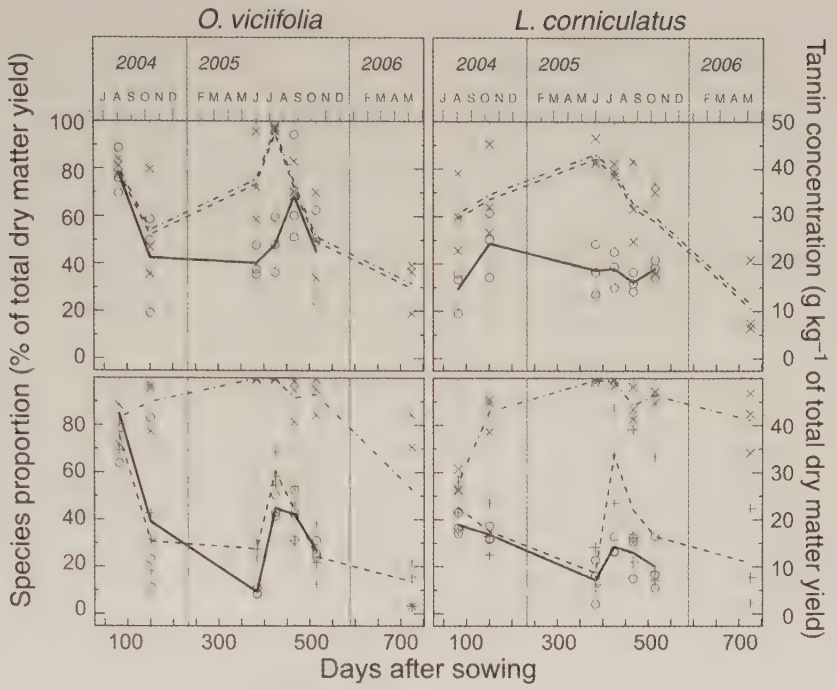
O. viciifolia
L. corniculatus
2004
2005
2006
J A S O N D
F M A M J J A S O N D
F M A M
Species proportion (% of total dry matter yield)
Tannin concentration (g kg⁻¹ of total dry matter yield)
Days after sowing

Figure 2. Mean proportion of sown species (dash-dotted line, $n = 3$), mean proportion of tanniferous species (dashed line, $n = 3$) as a percentage of the total DM yield, respectively, and the mean tannin concentration of individual yields (solid line, $n = 3$) in the course of the experiment. Upper row: purely sown stands of *O. viciifolia* cv. Visnovsky, *L. corniculatus* cv. Lotar. Lower row: the same species and cultivars as above but sown in a mixture with the grass *F. pratensis*. Original data on the plot level are presented as symbols (i.e. × = sown species, + = tanniferous species, ○ = tannin concentration).

C. intybus: 14) than in dried plant material (*O. viciifolia*: 92; *L. corniculatus*: 26; *C. intybus*: 11).

Offered as dried forages (Fig. 3a), palatability indices during the first 10 days were higher for *O. viciifolia* (PI: 91.2 ± 23.9%) and *C. intybus* (PI: 84.3 ± 23.0%) than for *L. corniculatus* (PI: 65.5 ± 21.8%). However, mainly due to very low initial values, none of the tanniferous forages was as palatable as the control forage when averaged over the first 10 days (the PI of the control is defined as 100%). By increasing the energy and nutrient supply 10 days after the start of the experiment, we expected the wethers to indicate the palatabilities of the different feeds more differentiatedly. However, during the second 10 days, the palatability indices of all the tanniferous forages approximated that of the control (i.e. 100%) to an even greater extent (average PI: *O. viciifolia*: 95.6 ± 2.9%; *C. intybus*: 102.9 ± 13.5%; *L. corniculatus*: 100.2 ± 13.1%). Hence, the palatability of the dried tanniferous forages was very similar to that of the dried ryegrass/clover mixture.

Fed as ensiled forages (Fig. 3b), the palatabilities of *O. viciifolia* (151.9 ± 81.9%) and *C. intybus* (121.2 ± 69.0%) were clearly higher than that of the control feed during the first 10 days of the experiment. Only *L. corniculatus* (PI: 77.7 ± 33.3%) had a palatability index lower than the ensiled control forage. During the second 10 days, *O. viciifolia* (on average: 159.6 ± 51.2%) remained more palatable than the control forage. Palatability of *C. intybus* (100.6 ± 16.2%) and *L. corniculatus* (101.0 ± 44.5%), however, were similar to that of the control forage.

The average palatability indices showed a high variation both among individual animals and between days. This variation was greater for ensiled than for dried forages, possibly due to the shorter evaluation time for the ensiled forage (7.5 min for ensiled forages versus 15 min for dried forages). In the case of dried tanniferous forages, palatability was initially low compared to controls. Already 2–3 days after the start of the experiment, however, the palatability of dried tanniferous forages did not differ from that of the familiar non-tanniferous control forage. Within this short period of time, adaptations in the wether's physiology or rumen flora, to avoid potentially detrimental effects of condensed tannins, are highly unlikely. It seems more plausible that the initially low but strongly increasing palatability indices indicate beneficial postingestive feedbacks or simply reflect a sensory customization to the unfamiliar diets. Wethers needed no time to become accustomed to ensiled tanniferous forages. They were at least as palatable as the control feed immediately after the start of the experiment.

It is concluded that after 2–3 days, and independent of the conservation method used, all tested tanniferous forage plants were at least similarly palatable as an equally conserved ryegrass/clover mixture. Ensiled *O. viciifolia* had the highest tannin concentrations of all the tested diets and regardless of its elevated tannin concentrations was clearly more palatable to the wethers than an ensiled ryegrass/clover mixture. Therefore, *O. viciifolia*, especially in its ensiled form, is considered the most promising

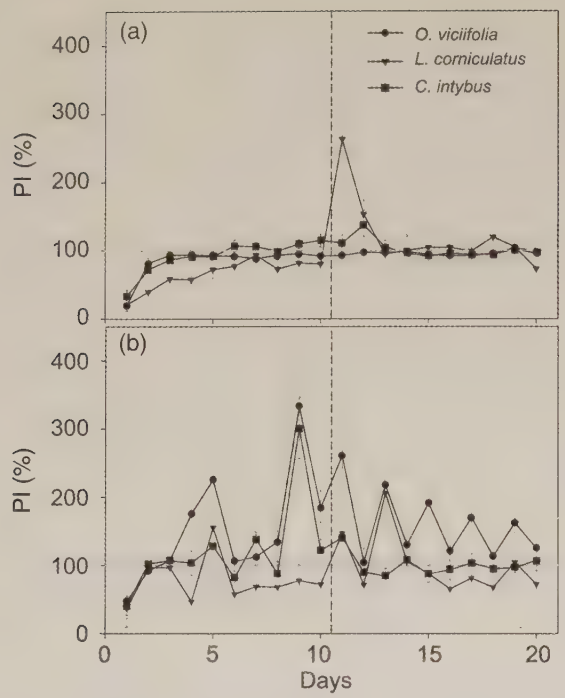

Figure 3. Palatability indices (PIs) of (a) dried or (b) ensiled tanniferous forage plants compared to a dried or ensiled non-tanniferous ryegrass/clover mixture (control), respectively. The palatability index of the control is defined as 100%. Tanniferous forages for which the palatability index exceeds 100% are more palatable to wethers than the control. From day 1 to 10, feeds covered 110% of the maintenance energy requirement. After day 10 (dashed line), energy supply was increased to 155% of the maintenance energy requirement (see the Methods section).

candidate for a practical application against gastrointestinal nematodes.

Antiparasitic activity of O. viciifolia *hay or silage*

The tannin concentrations of *O. viciifolia* hay and silage were 62 g kg^{-1} DM and 41 g kg^{-1} DM, respectively. Compared to their respective control groups, marked reductions in the combined fecal egg counts of *H. contortus* and *C. curticei* were observed when *O. viciifolia* was fed as hay or silage (Fig. 4). Within the 16-day feeding period, fecal egg counts decreased by 58% when lambs were fed with *O. viciifolia* hay, whereas fecal egg counts increased by 43% when lambs were fed with the control hay. For *O. viciifolia* silage, faecal egg counts were reduced by 37%, whereas in the corresponding control group fecal egg counts increased by 16%.

In comparison to the results of freshly administered *O. viciifolia*[53], the antiparasitic properties of *O. viciifolia* were largely preserved in both silage and hay, leading to a substantial decrease in worm egg excretion in feces. Our results suggest that the ensuing pasture contamination with infective larvae will decrease considerably and re-infections will be reduced when sheep are fed with *O. viciifolia*.

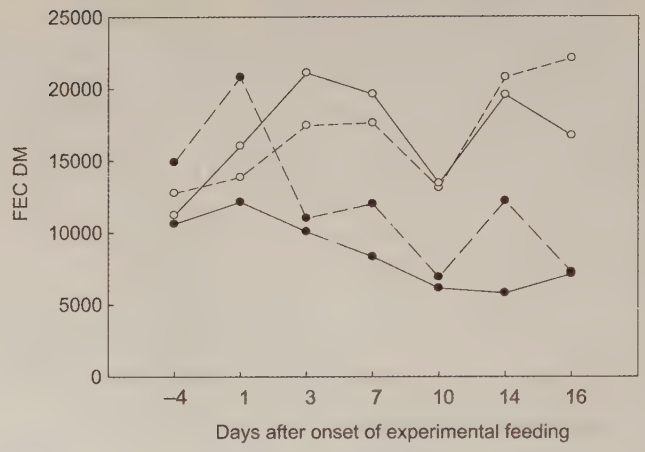

Figure 4. Mean parasite egg counts per gram dried feces (FEC DM; $n = 6$) of lambs either fed with *O. viciifolia* (closed symbols) or non-tanniferous control forage (open symbols), each administered as hay (dashed line) or silage (solid line), respectively.

Synthesis

O. viciifolia (cv. Visnovsky), *L. corniculatus* (cv. Lotar) and *C. intybus* (cv. Grasslands Puna) appeared particularly suitable for cultivation under the given temperate climatic conditions, whereas *L. pedunculatus* was competitively weak, possibly because this species prefers more humid than 'average' agronomic conditions. Similar performances of these species have been observed in an independent cultivation trial at Frick, Switzerland[53]. With regard to their tannin concentrations, only *O. viciifolia* and *L. corniculatus* seemed promising candidates for the control of gastrointestinal nematodes in ruminants, whereas tannin concentrations of *C. intybus* were very low. Nevertheless, *C. intybus* has repeatedly been reported to have anthelmintic and other desirable properties possibly related to elevated concentrations of other secondary metabolites (e.g. sesquiterpene lactones) found in this species[3].

Our field experiment demonstrated that the competitive ability of even the most promising tanniferous candidate plants (i.e. *O. viciifolia* cv. Visnovsky and *L. corniculatus* cv. Lotar) was suboptimal. As a consequence, seasonal fluctuations of tannin concentrations can, to a large extent, be attributed to shifts in the relative contribution of tanniferous plant material to total yield, even in purely sown swards. Pronounced short-term fluctuations in tannin concentrations of harvestable biomass (e.g. *O. viciifolia*, +79% within 17 days)[53] can result from differences in momentary growth rates between sown tanniferous plant species and their (sown or unsown) non-tanniferous neighbors. Additionally, fluctuations of tannin concentrations in pure stands can result from shifts in leaf/stem ratios of tanniferous forage plants during their development[14]. This implies that with regard to the suggested breeding of tannin-rich plants[1], a high competitive ability and a large leaf to stem ratio[14] are parameters likely to be just as important in enhancing the tannin concentration of

harvestable biomass as an elevated intrinsic tannin concentration of the leaves of a cultivar.

With regard to the cultivation and management of tanniferous forage plants, mixtures were found to have clear advantages in relation to the total DM yield and in suppression of unsown species. Future research should focus on how to profit from the advantages of mixtures without suppressing tanniferous plants and lowering tannin concentrations. Possible options are (i) to lower nitrogen input to increase the competitive advantage of the tanniferous legume relative to the grass competitor, (ii) to reduce sowing densities of the grass, or (iii) to test mixtures with other grasses (e.g. short-bladed and slow-establishing grasses such as *Agrostis alba* or *Festuca rubra*). Alternatively, one could try to enhance the performance and reduce weed invasion in monocultures of tanniferous forages, for example (iv) by increasing sowing densities or (v) by adapting cutting frequencies to the tanniferous species.

Parallel to optimizing the cultivation and concentration of condensed tannins in the target candidates, investigations on the acceptance of these plants by sheep are of major importance. The feeding and palatability experiment showed that 2–3 days after the start of the experiment, the palatability of tanniferous forages was at least similar to a ryegrass/clover control, independent of the conservation method used. Regardless of its comparatively high tannin concentration, ensiled *O. viciifolia* was the most palatable among the tested forages. There was no evidence of negative side effects on the wethers from any of the tanniferous forages. Across species, the palatability of the different forages appeared unrelated to their tannin concentrations. If condensed tannins as 'plant defensive compounds'[15,17,18] should deter herbivores, they do not seem to have acted through a depressing effect on palatability or short-term physiological feedbacks in our experiment. It is also possible that the apparent lack of a 'plant defensive effect' of condensed tannin in this study was caused by interactions with other nutrients[11,54] or different chemical structures and 'potency' of tannins in the tested plant species[5]. In this context, the multitude of potentially influential chemical features of tannins and the great variety of suggested methods to analyze them contrasts with the fact that we still lack a simple but useful principle to interlink the chemical structure and the biological activity of tannins[5,11,55].

Apart from the general interest in the potential advantages and disadvantages of tanniferous forages for ruminant metabolism, the present study was primarily aimed at preparing a pathway towards their use against gastrointestinal nematodes. Administering of hay or silage of *O. viciifolia* to lambs co-infected with *H. contortus* and *C. curticei* reduced the combined fecal egg output markedly compared to the controls. As trichostrongylidosis (i.e. the disease caused by gastrointestinal nematodes) is a pasture-borne disease, a reduced contamination of the pasture with parasite eggs and infectious L3 larvae is likely to diminish the risk of renewed infections. Besides the effect on fecal egg output, there is strong evidence for a direct lethal effect of *O. viciifolia* on *H. contortus*[47,53], the species with the highest pathogenicity among the gastrointestinal nematodes of temperate and (sub)tropical regions[47].

Conclusions

The satisfactory yield and competitive ability of *O. viciifolia*, its high palatability despite its elevated tannin concentration and its efficacy against gastrointestinal parasites even in a conserved form would appear to make this tanniferous plant species an ideal candidate for the implementation of a non-pharmaceutical control strategy against gastrointestinal parasites. With regard to forage conservation, ensiling seems preferable to drying because it minimizes the loss of tannin-rich leaves, allows forage conservation relatively independent of the weather and, according to our results, does not diminish the palatability to sheep or the efficacy against intestinal parasites.

Further research is needed to improve our understanding of the relationship between the chemical features of the condensed tannins and their biological activity. In particular, it is essential to clarify the mode of action by which condensed tannins exert antiparasitic effects in sheep. Future studies should aim to enhance efficacy against gastrointestinal nematodes by focusing on the possibilities of increasing concentrations of condensed tannins in the offered forage without reducing the palatability or nutritional quality of the feed. Finally, a control strategy against gastrointestinal nematodes based on condensed tannins needs to be adapted to optimize its technical and economical practicability for employment and acceptance on private sheep farms.

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Energy self-reliance, net-energy production and GHG emissions in Danish organic cash crop farms

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Abstract

Organic farming (OF) principles include the idea of reducing dependence of fossil fuels, but little has been achieved on this objective so far in Danish OF. Energy use and greenhouse gas (GHG) emissions from an average 39 ha cash crop farm were calculated and alternative crop rotations for bio-energy production were modeled. Growing rapeseed on 10% of the land could produce bio-diesel to replace 50–60% of the tractor diesel used on the farm. Increasing grass-clover area to 20% of the land and using half of this yield for biogas production could change the cash crop farm to a net energy producer, and reduce GHG emissions while reducing the overall output of products only marginally. Increasing grass-clover area would improve the nutrient management on the farm and eliminate dependence on conventional pig slurry if the biogas residues were returned to cash crop fields.

Key words: biogas, energy, life cycle assessment, greenhouse gas, rapeseed, crop rotation

Introduction

Fossil fuel energy use and the resulting greenhouse gas (GHG) emissions from food production, transport and consumption contribute significantly to global warming[1]. However, agriculture may contribute to the reduction in GHG emissions by replacing fossil fuel energy used for transport, heating and electricity production with biomass from perennial crops such as grass[2], willow[3], coppice[4] or seasonal crops (e.g. rapeseed, maize)[5–7]. Many of these crops are efficient in terms of reducing GHG emissions, but the studies also show that the total environmental effect of substituting fossil fuel with bio-energy depends on a systems analysis (e.g. whether the indirect energy use of producing the biomass is included). The indirect energy and GHG emissions embodied in inputs like fertilizer are significant in the CO_2-emission balances. Therefore, an environmental assessment of bio-energy should include the direct use of energy on farm and the embodied (indirect) energy in inputs used in farm biomass production for electricity and biofuels[2,3,6].

In response to the European Union's goal of increasing the contribution of biomass to overall energy supply the European Environmental Agency (EEA) analyzed the potential for supplying environmentally compatible bio-energy from agriculture[7]. It was concluded that agriculture may contribute up to 47 million tons of oil equivalents, which would account for one-third of the target in the EU Commission's Biomass Action Plan (BAP). A significant part of biomass energy should come from the cultivation of set-aside land while EEA assumed that cuttings from grassland would contribute 6–7%. However, the EEA stresses that '*in order to prevent environmental pressure from the agricultural sector due to more intensive farming [the] study assumed that there will be a high share of environmentally-oriented farming with lower yields*'. Organic agriculture is considered as one type of environmentally friendly farming system[8,9], which combines lower emissions of nutrients per hectare with the maintenance of biodiversity[10,11]. Thus, organic agriculture might play a role in the future bio-energy supply. However, the question of nutrient supply needs to be solved as organic crop rotations with a high percentage of seasonal crops often result in comparably low yields.

The original principles of organic agriculture included goals of reducing dependence on fossil fuel and other limited resources[12] and this is still an explicit part of the objectives of the Danish organic farming (OF) movement. Due to, among others, the non-use of synthetic fertilizers, energy use is usually lower in OF compared with

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Table 1. Area and yield of crops for three organic farm scenarios[1] representing an average Danish cash crop rotation and two crop rotations with bio-energy crops.

Crop	Yield ha^{-1}	Scenario:	Base[2] 1	Rapeseed[1] 2	Grass–clover 3
Spring barley	3100 kg		13.9	13.4	13.6
Winter wheat	4610 kg		3.6	3.6	3.6
Rye	2530 kg		2.4	2.4	2.4
Oats	3040 kg		2.4	2.4	2.4
Peas	2170 kg		1.9	1.9	1.9
Winter rapeseed	1760 kg		0	3.9	0
Barley for silage	4300 FE[3]		4.0	4.0	4.0
Grass–clover (rotation)	5600 FE		4.2	4.2	7.8
Permanent grassland	2000 FE		3.3	3.3	3.3
Set-aside land			3.3	0	0
Sum			39.0	39.0	39.0

[1] Base, rapeseed and grass–clover denote farm scenarios.
[2] Average yield and area of crops estimated from organic cash crop farm database on sandy soil in Denmark.
[3] One feed unit (FE) corresponds to the energy value of 1 kg cereal for cattle (~1 kg DM grass–clover and 1.2 kg DM whole crop barley silage).

conventional farming methods, both per hectare and per unit of crop or livestock produced[13–17]. Typically, the fossil energy use per hectare in organic crops is lower compared with conventional crops but yields and stocking density are also lower.

The difference in the use of fossil fuel energy per kg of product between OF and conventional farming systems is often marginal and many OF systems still depend on import of non-renewable energy sources (diesel and electricity). The question of reducing the dependence on fossil fuels in organic agriculture has not been addressed extensively, nor has the potential for organic agriculture to contribute to bio-energy production for society. Jørgensen et al.[4] discuss the potential for using alder (*Alnus* spp.) as an energy crop in organic farms. Alder may bind atmospheric N_2 through symbiotic biological N fixation and can be used for combined heat and electricity production. This perennial crop may also offer other societal benefits such as protection of ground water resources, receiving municipal wastewater and/or be combined with high welfare livestock keeping with intensive livestock production. Fredriksson et al.[18] compared three scenarios for self-sufficiency in on-farm produced bio-based tractor fuels and found that rape methyl ester (RME) had the better energy efficiency compared with ethanol produced from wheat and biogas from leys. Producing and using biogas for traction would require unrealistically large, high-pressure storage facilities on the farm to meet peak season demand. The authors recommended that biogas be used for electricity production instead.

Given this background it is interesting to explore the possibilities for changing organic farms into net-energy producing units by combining food and energy production[19]. OF may develop energy-sustainable agricultural systems including bio-energy crops for environmentally sensitive areas and at the same time improve the crop rotations on cash crop farms. This paper will focus on grass–clover leys for biogas-based electricity and rapeseed oil as replacement for tractor diesel.

Methodology

The study consists of three steps: (1) establishing a representative model of Danish organic cash crop farms, (2) modeling the crop yield and energy conversion from introducing bio-energy crops in the rotation and (3) assessing the total energy and nutrient balances at the farm level.

An average organic cash crop farm on sandy soil in Denmark was established as the base farm from a representative farm database[20]. The organic cash crop farm type consisted of the 107 accounts from certified organic farms without dairy production on sandy soil, representing 1084 farms with a total area of 42,287 ha in the base year 1999. The acreage in each crop, the crop yield, livestock production, sales and manure import used in the base scenario were averages from the dataset. Minor crops were not included in the model. Other inputs such as the use of electricity, diesel, manure and feed import were modeled from the crop and livestock production as described in Dalgaard et al.[15,20]. The feed import was modeled as the standard feed requirements for organic beef cattle less the amount of home grown feed from leys and cereals[26]. The manure import was calculated according to Danish rules for OF, which limits the total application of manure to 140 kg N ha^{-1}, part of which may be of non-organic origin. The amount of manure imported was checked against national statistical data[20].

The average crop rotation in the base scenario (scenario 1) included only 11% grass–clover and 5% pulses (Table 1). The rest of the 39 ha were seeded to cereals, thus reserving only a small proportion of the land to nitrogen fixing crops. The grass–clover leys and the permanent grassland

were used for beef cattle production (12 livestock units). The cattle were supplemented by 7.6 tons of imported rapeseed cake. The 9% set-aside land was not used and had traditionally little content of legumes. The average farm imported 4.4 tons of nitrogen with manure from organic dairy farms and conventional pig farms. Nitrogen and phosphorus balances were calculated according to Kristensen et al.[21] and Halberg et al.[22] Ammonia losses were estimated according to Andersen et al.[23] and denitrification followed Vinther and Hansen.[24] The nitrous oxide and methane emissions were calculated according to IPCC[25], but using a country-specific accounting method for some of the crop residue N content[26]. The net change in soil N content was estimated using the model C-tool[27] and potential nitrate leaching was estimated as the difference in N-surplus, gaseous losses and net soil-N change[28].

The crop rotation in scenario 1 is not ideal from an agronomical point of view, because of the relatively weak nutrient re-cycling and the high proportion of cereals, which is also the reason for the dependence on imported conventional manure. Low soil fertility, especially on sandy soils, and limited nutrient supply on organic farms are linked with low crop yields and high weed pressure[29–31].

Two alternative scenarios were simulated aiming at improved energy self-reliance in the organic cash crop farms. One alternative consisted of producing biofuel for traction from rapeseed on the farm using a low-technology method suitable for individual farms (scenario 2). Rapeseed oil can replace tractor diesel after a slight modification of the engine[32] by using a farm scale cold press system that extracts 30% of the oil content[33,34]. According to Bjerg[35] the energy content was estimated to be 35 MJ kg^{-1} oil corresponding to 32 MJ $liter^{-1}$ [36]. Because rapeseed is a difficult crop to grow in organic rotations in Denmark due to a high nitrogen demand and risk of crop loss due to insects and soil borne diseases, the area with this crop should not exceed 10% of the crop rotation. The yield of the 3.9 ha winter-sown rapeseed was estimated at 1760 kg ha^{-1} from the data (Table 1). The rapeseed cake (70% of rapeseed weight) after oil pressing was used as cattle feed and thus replaced most of the purchased rapeseed cake (Table 2). The manure import was identical to the baseline scenario.

In a third scenario the potential gain from biogas production and recycling of nutrients from an extra 10% grass–clover leys in the crop rotation was estimated. This model included a medium-sized biogas plant within 25 km from the farm, transporting the green mass from the fields in a 28 ton truck and returning (in another truck) the nutrient-rich effluent after digestion. In total 22.4 tons of dry matter (DH) was removed from the grass–clover leys for biogas and 2.3 tons N returned from the biogas plants replacing the imported pig slurry as fertilizer in the cereal crops (Table 2). Thus, the crop rotation in scenario 3 did not depend on non-organic manure because of increased area with biological nitrogen fixation and improved recirculation of nutrients compared with scenario 1. The

Table 2. Inputs used and outputs produced in three scenarios[1] for Danish organic cash crop farms with bio-energy crops.

Product	Scenario:	Base 1	Rape-seed 2	Grass–clover 3
Purchased inputs				
Diesel (liter)		3226	1251	3092
Electricity (kWh)		9446	9698	9446
Lubricating oil[2] (liter)		323	328	310
Rapeseed cake (tons)		7.6	2.8	7.6
Barley (tons)		0.0	1.8	1.0
Pig and cattle manure (tons N)		3.4	3.4	1.1
Biogas effluent[3] (tons)				2.3
Sales				
Cereals (tons)		58	58	58
Peas (tons)		6	6	6
Beef (tons live weight)		9	9	9
Grass-clover (tons DM)		0	0	22.4

[1] Base, rapeseed and grass–clover denote farm scenarios.
[2] Relatively large amount of oil corresponding to older machines.
[3] Returned nutrients from the biogas plant, see text for explanation.

methane (CH_4) biogas yield from grass–clover digestion was estimated at 0.35 kg CH_4 kg^{-1} organic DM[37], which is comparable with Fredriksson et al.[18] A net loss of 3% of the methane was subtracted (and included in GHG emissions) with the remainder converted on-site to electricity, which was supplied to the public net. It was assumed that the additional heat generated in the generator was utilized for either local feed processing or heating of houses in a nearby village, which is a typical situation for Danish biogas plants. An estimated 5% of the electricity and 10% of the heat generated was used for pre-heating and handling of grass–clover and was thus omitted from the net-energy calculation.

In order to get conservative estimates of bio-energy production the crop yields in the scenarios 2 and 3 were assumed to be identical to the base model (scenario 1) even though the improved crop rotations would suggest (small) yield increases (see Discussion). The area for bio-energy crops was primarily taken from the set-aside land, subsequently the spring barley area, which was only slightly reduced compared with the base model (Table 1). Therefore, the total production of cash crops and meat were almost identical in the three scenarios (Table 2).

The energy balances and the GHG emissions in the base model and bio-energy scenarios were estimated using the principles of Life Cycle Assessment (LCA) methodology[38,39] and coefficients from Nielsen et al.[40] and Dalgaard et al.[20] The inputs of fossil energy in the three models are shown in Table 2. The estimates of direct energy use included all field operations and on-farm transport, transport to and from the biogas plant and transport of imported manure and biogas effluent. Moreover, GHE emissions from the production of farm inputs

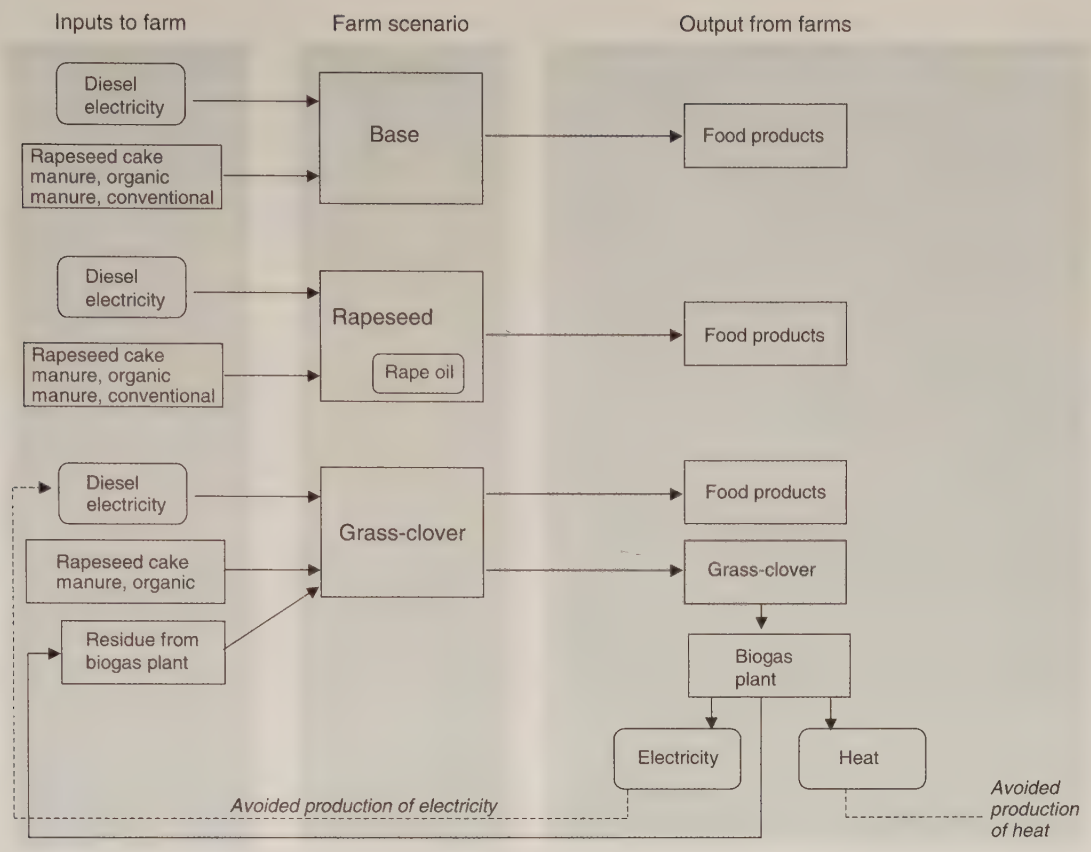

Figure 1. Systems delineation of inputs and outputs in the LCA of three scenarios based on an average Danish organic cash crop farm.

such as electricity and rapeseed cake were also included in the inventory.

In LCA the resource use and environmental impact aggregated across the product chain are calculated per functional unit, such as kg cereal or beef produced. In order to avoid unnecessary complications the energy use and emissions in the farm models were not allocated among the main products from the farm. However, the farm unit in the three scenarios produced the same total output of 58 tons of cereal, 6 tons of peas and 9 tons of beef (live weight), which facilitates a comparison of energy balances and environmental effects between the models. The small reduction in cereal area in scenarios 2 and 3 was compensated by importing an equivalent amount of organic barley (Table 2). The energy use and environmental impacts from this production outside the cash crop farms were included using data from Nielsen et al.[40] and Dalgaard et al.[20] Figure 1 illustrates the systems delimitation for the LCA.

When calculating the net energy balances and the total emission of GHG from the three scenarios it was necessary to account for the saved production of electricity and heat when using the biogas for combined electricity and heat production. This was estimated based on assumptions that a certain part of the Danish electricity production based on fossil fuels was replaced by the bio-energy. A standard value of 9.5 MJ kWh^{-1}, was used, which represents non-optimal fossil electricity production in Denmark[15]. However, electricity in Denmark is often produced in a combined gas driven power plant, where the heat is used for houses. Therefore, in the alternative calculation, 'Grass clover II', a more efficient electricity production system using only 5 MJ kWh^{-1} was assumed. This reduced both the energy cost in MJ per kWh of imported fossil electricity and the saved energy costs from the electricity exported from the biogas plant. Thus, the fossil energy cost for electricity used on the farm was assumed to be the same as for the replaced electricity production.

The use of crops for bio-energy was considered to be CO_2-neutral, which is a standard methodology[2,5,18]. Thus, the CO_2 emission from the combustion of the rape oil or digestion of the grass–clover was not larger than the CO_2-sequestration during crop growth. The change in soil C content was not included in the CO_2 balances. Methane and nitrous oxide emissions were converted to CO_2 equivalents (CO_2E) by multiplication by 20 and 320, respectively, in accordance with standard methodology in LCA[39] and in climate change inventories[25].

Results and Discussion

Energy balances

Table 3 shows the energy balance of the average farm before and after the modeled alternative crop rotations. OF uses between 90 and 110 liters of diesel per hectare for field

Table 3. Energy use and production[1] (GJ yr^{-1}) for three scenarios for Danish organic cash crop farms with bio-energy crops.

Scenario:	Base 1	Rapeseed[5] 2	Grass–clover 3a	Grass–clover 3b
Direct and indirect energy use (GJ)				
Diesel	129	50	124	124
Electricity[2]	90	92	90	47
Rapeseed cake	1	0.2	1	1
Transport of grass and effluent	0	0	15	15
Other[3]	0	2	1	1
Sum	220	145	231	188
Replaced energy production (GJ)				
Heat produced in electricity production[4]	0	0	111	111
Electricity production[2]	0	0	247	130
Sum	0	0	358	241
Net energy consumption (GJ)	220	145	−127	−53

[1] All farms export 58 tons of cereals, 6 tons of pulses and 9 tons of beef (live weight).
[2] The fossil energy cost for electricity used on the farms is assumed to be the same as for the replaced electricity production, see Methods section for details.
[3] A small import of cereals was included in the models to compensate for the reduced barley area, so that all farms deliver the same amount of products.
[4] Assuming that the heat generated from the electricity production is used efficiently, which is questionable—see text for discussion.
[5] Base, rapeseed and grass–clover denote farm scenarios.

operations, accounting for 59% of the total energy used in the average cash crop farm (base scenario, Table 3). An average rapeseed yield of 1800 kg ha^{-1} would be enough to replace 50–60% of the diesel used on the farm. The rapeseed cake co-product would replace 64% of the input of concentrate for the farm's livestock production but the indirect energy use saved from this was counterbalanced by the increased electricity needed for the pressing process (Table 3). The fuel/feed use of the rapeseed crop without industrial processing may be the reason for our positive evaluation in contradiction to the assessment of conventional rapeseed for biofuels by Hanegraf et al.[5] To replace the total diesel use on the average organic cash crop farm would require either a yield of 2800 kg rapeseed per hectare on the 10% of the land or greater oil extraction rates, which may in fact not be unrealistic in winter-sown rapeseed in the future. Another option for utilizing the energy yield from rapeseed exists, namely the conversion of oil to RME. Fredriksson et al.[18] found that an organic cash crop farm would be self-sufficient in bio-fuel production if 9.3% of the land was grown with rapeseed for RME. They assumed a yield of 2000 kg rapeseed per ha and 68% oil extraction efficiency which resulted in a net energy production in fuel of 18.5 GJ ha^{-1} compared with 14.6 GJ ha^{-1} in our study. However, the transesterification in itself does not yield more energy from rapeseed oil and the process depends on electricity and external chemical inputs including a supplement of methanol. Therefore, we consider the use of cold pressed oil directly in the tractor as more in line with organic philosophy. Fredriksson et al.[18] also found that RME would be more efficient compared with wheat-based bioethanol and biogas as home produced biofuel in OF and conclude that biogas is more suitable for electricity production, which agrees with our study.

Increasing the area with grass–clover from 10 to 20% of the crop rotation (in the scenario 3) gives a surplus of DM, which could produce 7840 m^3 of biogas. When using the biogas for a combined generation of electricity and heat, the grass–clover yielded more than 2.5 times the electricity used on the cash crop farm (247 GJ versus 90 GJ, Table 3). This corresponds to approximately 2600 kWh from 3.9 ha grass or enough to cover the electricity in 5–6 Danish households. The generated 111 GJ of heat (as a by-product of electricity production from the biogas) may be used for producing feed-mixtures, evaporating water from the degassed grass effluent or for heating houses in a village through pipelines (a type of centralized heating system very often used in Denmark already). Assuming that all electricity and heat is utilized for purposes where it saves fossil fuel energy, the farm will be a net energy producer (also after deduction of the 15 GJ energy used for transport of grass and de-gassed grass-effluent to and from the central biogas plant, Table 3). Contrary to the rapeseed oil this energy was not produced nor used on the farm, but farm scale biogas production is a possibility[18].

The conversion between kWh and GJ depends on how efficient the marginal electricity production is (i.e. the type of fossil energy saved when bioelectricity is generated). This assumption was tested with different values as shown in the scenarios 3a and 3b in Table 3. If the electricity replaced was of a more efficient type, then the net energy gain from the farm would be 53 GJ or 28% of the energy used on the farm. From Table 3 it also appears that if only 50% of the generated heat was utilized then the net energy gain in the grass–clover scenarios would be reduced to 72 and 0 GJ, respectively. However, it would be agronomically possible to combine the rapeseed and grass–clover energy crops into one scenario, in which case the

Table 4. Emissions of GHG for the three scenarios[1] for Danish organic cash crop farms with bio-energy crops.

Tons CO_2E farm^{-1} yr^{-1} Scenario:	Base 1	Rape-seed 2	Grass–clover I 3
Nitrous oxide	82	82	82
Methane from farm and biogas plant	13	13	16
CO_2 from diesel	12	5	12
Import electricity and rapeseed cake	8	7	8
Transport of grass and effluent	0	0	1
Replaced electricity production[2]	0	0	−17
Replaced heat production[3]	0	0	−10
Sum	115	107	92

[1] Base, rapeseed and grass–clover denote farm scenarios.
[2] See note 2 in Table 3.
[3] See note 4 in Table 3.

farm would be self-sufficient with energy. But such a scenario would then use 19% of the farm's land for energy production, which would reduce total yield of food crops. The economical and political implications of such a change in agricultural land use is beyond the scope of this study, but does seem to be within scenarios considered politically acceptable in the EU[7].

Emission of GHG

Table 4 shows the estimated GHG emissions in CO_2E. Nitrous oxide emitted from the farms contributed the larger part (69–77%) of total on-farm GHG emissions and equals 82 tons CO_2E for all three scenarios. Denitrification of leached nitrate accounted for 26–35% of nitrous oxide emissions. Less nitrate (46 kg N ha^{-1}) was leached from the 'grass–clover scenario' compared to the other two scenarios (both 61 kg N ha^{-1}) (Table 5). Also less N_2O (22 kg CO_2E) from denitrification of nitrate was emitted from the 'grass–clover scenario' compared to the other scenarios (both 29 kg CO_2E). However, the N_2O emissions from biological nitrogen fixation and crop residues were higher on the grass–clover scenario (29 kg CO_2E) compared to the other scenario (both 22 kg CO_2E), thus the total nitrous oxide emissions and nitrate leaching in the 'grass–clover scenario' was counterbalanced by higher biological nitrogen fixation and crop residues (Table 4).

The effect of biogas production was a reduction of total GHG emissions from 115 to 92 tons CO_2E (20%) if assuming unchanged nitrous oxide emissions and including the effect of replaced fossil energy use for electricity. Further studies are needed to determine the degree of uncertainty in these estimates.

Table 5. Field-level nitrogen balances (kg N ha^{-1}) of three scenarios[1] for Danish organic cash crop farms with bio-energy production.

Product Scenario:	Base 1	Rape-seed 2	Grass–clover 3
Input			
Imported manure[2]	87	87	28
Effluent, returned from biogas			59
Own manure	26	26	26
Biological nitrogen fixation	28	28	42
Atmospheric deposition	16	16	16
Total	157	157	171
Output			
Cash crops	28	28	47
Livestock fodder	28	28	28
Total	56	56	75
Field level surplus	101	101	96
Losses			
Ammonia	11	11	11
Denitrification	14	14	14
Net soil-N gain	15	15	25
Potential leaching	61	61	46

[1] Base, rapeseed and grass–clover denote farm scenarios 1, 2 and 3.
[2] N imported in slurry from pig and dairy farms. In the 'grass–clover' scenario the N in residues from biogas plant replaced an equivalent amount of N in imported manure (mostly conventional pig slurry).

The CO_2 balances from crop production and bio-energy use in the different scenarios were not included in the GHG emissions and were treated as neutral. This probably underestimated the net improvements in CO_2 balances of the bio-energy systems compared with the fossil fuel system because the CO_2-sequestration in the roots and stubble of the grass–clover crop will contribute to a (higher) net build up of soil-carbon, which is not emitted in the bio-energy production. The net soil organic matter gain in the different rotations was not included directly in the calculations of GHG emissions. However, using the calculated average net soil-N gain and a C/N ratio of 10, the extra C sequestration due to increased grass–clover area in scenario 3 amounts to approximately 100 kg C ha^{-1} compared with scenarios 1 and 2 (Table 5). This is equivalent to 367 kg CO_2 sequestered ha^{-1} y^{-1} or approximately 14.3 tons CO_2 on the 39 ha, which corresponds to a further 12% reduction in GHG emissions compared with scenario 1 (Table 4).

Nutrient balances and losses

Table 5 shows the nutrient balances and losses in the different crop rotations. There was no detectable difference between the base and the rapeseed scenario. Harvesting grass–clover for biogas and returning nutrients in the

'grass-effluent' to the cash crops (scenario 3) improved nitrogen cycling on the farm and reduced the need for imported conventional manure. The returned residues from degassed grass–clover thus replaced the imported conventional pig slurry in the grass–clover scenario. Because the biological nitrogen fixation was higher, the N input in scenario 3 was 9% higher compared to the base crop rotation (scenario 1). However, the export of N with grass–clover resulted in a 34% higher output and a slightly lower farm gate N-surplus (96 versus 101 kg N ha^{-1}). The potential leaching was reduced from 61 to 46 kg N ha^{-1} because the increased grass–clover area led to an increase in the average net soil-N gain through increased soil organic matter build-up.

As mentioned, the crop yields per ha were kept constant across the scenarios. However, in reality the improved crop rotation, nutrient recycling and the soil fertility improvement from grass–clover would probably increase the cereal yields and decrease weed pressure and diseases. In a parallel study[42] with the model FASSET[41] an increased proportion of grass–clover in an organic cash crop rotation improved soil fertility and nutrient cycling and resulted in approximately 10% higher cereal yields. The EEA states that the use of grassland cuttings for energy purposes may be a good opportunity to maintain the management of extensive farmland in order to preserve biodiversity (as an alternative to abandonment)[7]. In our study we assumed that the 3.3 ha permanent grassland would be used for grazing beef cattle. But in case of reduced grass needs on the farm, the permanent grassland could yield an additional 5–6 tons of DM for biogas production or a 25% increase compared to the grass–clover scenario.

The rapeseed and grass–clover crops were used as examples of the potential for energy self-reliance in OF. Even though they were modeled separately for simplicity, both could be implemented at the same time and complement each other in order to maximize energy self-reliance. Other crops such as coppice may prove to be more profitable and require less land in a long-term perspective[4], and it is eventually a normative question for the organic movement whether bio-energy should be produced and used on the farm.

Conclusion

Changing average organic cash crop rotations in Denmark to include 20% grass–clover and 10% rapeseed could serve the dual purpose of building soil fertility and delivering biomass for energy production for society or for energy self-sufficiency at the farm level. While this possibility has become more attractive at the farm level after the reform of the EU Common Agricultural Policy, there are a number of structural and organizational challenges to overcome, such as locating biogas plants at economic hauling distances from a concentration of organic farms and near a facility that may use the surplus heat produced.

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Modeling carbon cycles and estimation of greenhouse gas emissions from organic and conventional farming systems

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Abstract

The paper describes the model software REPRO (REPROduction of soil fertility) designed for analyzing interlinked carbon (C) and nitrogen (N) fluxes in the system soil–plant–animal–environment. The model couples the balancing of C, N and energy fluxes with the target to estimate the climate-relevant CO_2, CH_4 and N_2O sources and sinks of farming systems. For the determination of the net greenhouse effect, calculations of C sequestration in the soil, CO_2 emissions from the use of fossil energy, CH_4 emissions from livestock keeping and N_2O emissions from the soil have been made. The results were converted into CO_2 equivalents using its specific global warming potential (GWP). The model has been applied in the experimental farm Scheyern in southern Germany, which had been divided into an organic (org) and a conventional (con) farming system in 1992. Rather detailed series of long-term measuring data are available for the farm in Scheyern, which have been used for validating the software for its efficiency and applicability under very different management yet nearly equal site conditions.

The organic farm is multi-structured with a legume-based crop rotation (N_2 fixation: 83 kg ha^{-1} yr^{-1}). The livestock density (LSU = Livestock Unit according to FAO) is 1.4 LSU ha^{-1}. The farm is oriented on closed mass cycles; from the energetic point of view it represents a low-input system (energy input 4.5 GJ ha^{-1} yr^{-1}). The conventional farm is a simple-structured cash crop system, based on mineral N (N input 145 kg ha^{-1} yr^{-1}). Regarding the energy consumption, the system is run on high inputs (energy input 14.0 GJ ha^{-1} yr^{-1}). The organic crop rotation reaches about 57% (8.3 Mg ha^{-1} yr^{-1}) of the DM yield, about 66% (163 kg ha^{-1} yr^{-1}) of the N removal and roughly 56% (3741 kg ha^{-1} yr^{-1}) of the C fixation of the conventional crop rotation. In the organic rotation, 18 GJ per GJ of fossil energy input are bound in the harvested biomass *vis-à-vis* 11.1 GJ in the conventional rotation. The strongest influence on the greenhouse effect is exerted by C sequestration and N_2O emissions. In Scheyern, C sequestration has set in under organic management (+0.37 Mg ha^{-1} yr^{-1}), while humus depletion has been recorded in the conventional system (−0.25 Mg ha^{-1} yr^{-1}).

Greenhouse gas emissions (GGEs) due to fuel consumption and the use of machines are nearly on the same level in both crop rotations. However, the conventional system emits an additional 637 kg CO_2 eq ha^{-1} yr^{-1}, which had been consumed in the manufacture of mineral N and pesticides in the upstream industry.

Besides the analyses in the experimental farm Scheyern, the model has been applied in 28 commercial farms (18 org and 10 con) with comparable soil and climate conditions in the surroundings of Scheyern (mean distance 60 km). The program calculations are aimed at benchmarking the results obtained in the farming systems Scheyern; they are expected to disclose management-specific variations in the emission of climate-relevant gases and to rate the suitability of the model for describing such management-specific effects. In order to make the situation in the farms comparable, only the emissions from cropping systems were analyzed. Livestock keeping remained unconsidered. Due to lower N and energy inputs, clearly lower N_2O and CO_2 emissions were obtained for the organic farms than for the conventional systems.

The analyses have shown possibilities for the optimization of management and the mitigation of GGE. Our findings underline that organic farming includes a high potential for C sequestration and the reduction of GGEs. Currently, the model REPRO is tested by 90 farms in the Federal Republic of Germany with the aim to apply it in the future not only in the field of research but also in the management of commercial farms.

Key words: carbon cycle, farming system, modeling, global warming potential, C sequestration, greenhouse gas emissions, REPRO

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Introduction

The carbon budget of agricultural systems has been the focus of numerous studies on different scales, from the elucidation of molecular mechanisms in the C metabolism of plants up to the analysis of the influence of land use systems on biogeochemical C cycles[1–3]. Especially the dramatic rise of the CO_2 concentration in the atmosphere has led to a worldwide search for possibilities of C sequestration in agriculturally used soils and for the reduction of CO_2 emissions under specific soil, climate and management conditions[3].

A large number of research findings are available on the effect of management practices on C sequestration and CO_2 emissions. Experiments have shown that a considerable CO_2 reduction potential lies in reduced and zero tillage versus conventional tillage[2], in the growing of perennial legumes rather than cereals and maize[4] and in the conversion of arable land to grassland[5]. Some studies contain analyses of greenhouse gas emissions (GGEs) from complex production systems (for example organic versus conventional farming) on the basis of field experiments[3], experimental and commercial farms[6] or in model calculations with statistic data material[7]. However, so far few scientific studies have been published that deal with the analysis of C cycles in farming systems and the interrelated on-farm C fluxes between soils, plants, animals and the environment. This is surprising as C cycles, beyond their climatic relevance, are of major significance for the efficiency of production. The carbon input to the soil has a decisive influence on humus level, biological activities and soil structure, thus considerably controlling the biomass yield.

Especially systems with limited inputs like organically managed farms require a sufficient recycling of organic C in order to support the yield capacity of the soil.

In studies of the net greenhouse effect of farming systems, not only are CO_2 and CH_4 emissions important, but, due to their high specific greenhouse potential, also the site- and management-related N_2O emissions[8]. Model approaches have been elaborated for emission inventories on the farm level, which consider all relevant outputs[2,9]; however, on the basis of partly simplified model algorithms. An overall view of the net greenhouse effect of farming systems must take into account, beside the biological C fluxes, also technical C fluxes, i.e., all CO_2 emissions involved by the input of fossil energy. This comprises (see[10]):

- on-farm CO_2 emissions resulting from the use of diesel fuel, electrical power, solid fuels and other energy carriers (= direct energy input),
- CO_2 emissions from the industrial upstream sector for the manufacture and transport of fertilizers, pesticides and machines (= indirect energy input).

The present paper has the following aims, to:

- outline an approach to the modeling of C cycles in farming systems and to integrate the methods into a complex farming model,
- describe and validate the results computed by use of the model software in example farms of different structure and intensity and to evaluate the practicability of the program,
- come to conclusions on the influence of a given farming system on the greenhouse effect and on practicable reduction strategies for GGEs.

The investigations took place in the experimental farm Scheyern in southern Germany, where two management systems are practiced (organic and conventional) and in 28 commercial farms, also in the south of Germany.

The experimental farm Scheyern had been chosen as test farm for the model applications because here very detailed and scientifically profound data are available (management records, measuring data on C fluxes, C pools and GGEs), which are suited for validating the program.

In contrast to this, commercial farms do not dispose of comparable databases. The records in the experimental farm Scheyern were made independently of data sampled for the design of the model software. In Scheyern, under nearly equal site conditions, two completely different management systems were established: an organically run mixed farm and a conventional cash crop farm. The target was to analyze their effects on the agroecosystem[11].

The primary target of the application is to test its efficiency and validity, to juxtapose computed and measured results, to check the sensitivity of the software for the consequences of management activities and to find out to which extent the results allow an interpretation.

The application of the program in 28 commercial farms is to benchmark the results obtained in the experimental farm Scheyern on a larger scale, to disclose management-specific variations in the GGEs and to evaluate the aptitude of the model for depicting such management effects. In order to make these farms with their highly different structure comparable, only emissions from the cropping systems were analyzed; livestock keeping was not considered.

The studies were based on the hypothesis that (1) modeling C cycles contributes to a better understanding of farming systems, thus providing the preconditions for an emission inventory; (2) farming systems have a particular importance for the implementation of CO_2 reduction strategies, because climate-related management decisions are due to be made on farm level; (3) tools for the analysis of C cycles have to be integrated into complex management systems, in order to estimate the ecological and economic effects of climate-protecting measures and to assess their feasibility.

Methods and Materials

Modeling approach

In the described investigations C cycles on farm level were depicted by using the computer program REPRO (REPRO-duction of soil fertility[12,13]). REPRO is software for analyzing, evaluating and optimizing the environmental

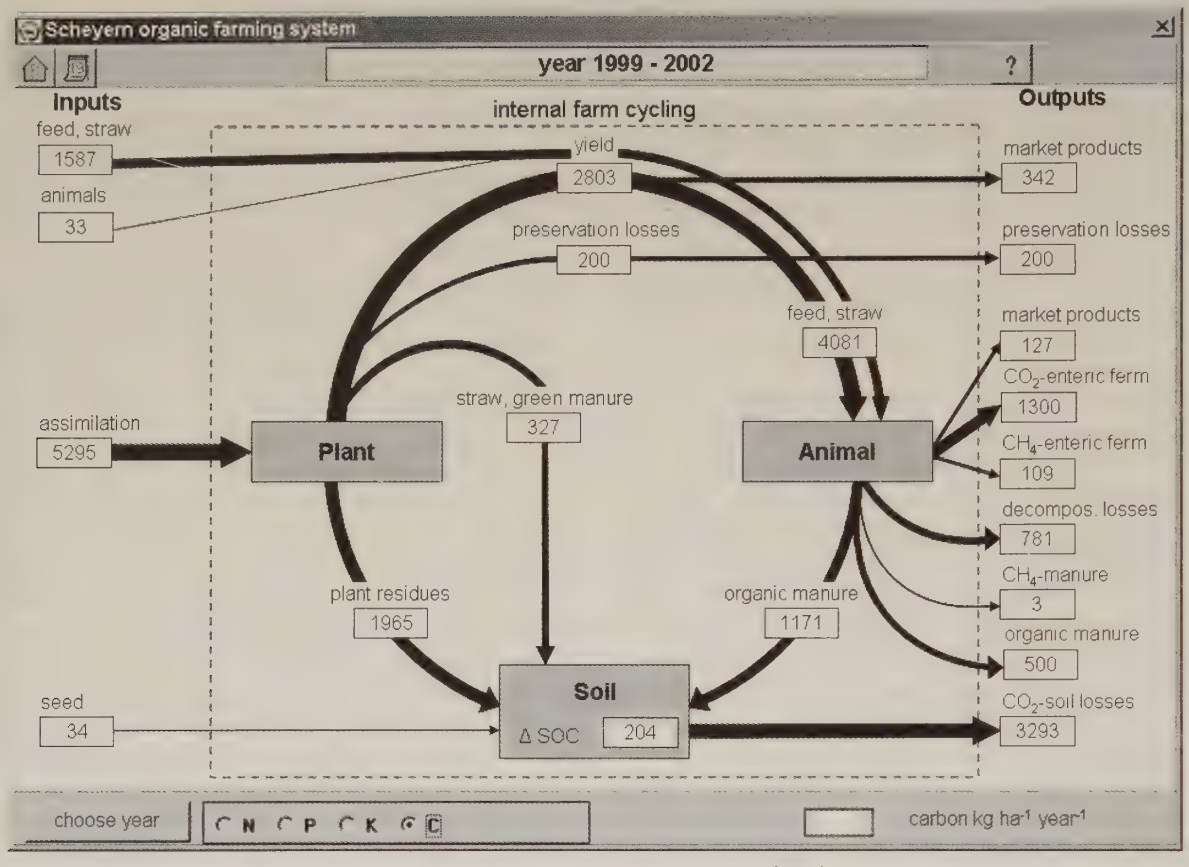

Figure 1. On-farm carbon cycle of the organic farming system Scheyern, kg C ha^{-1} yr^{-1} (av. 1999–2002), screenshot of the model REPRO.

effects of agricultural enterprises. The model describes a given farm as a functioning system. REPRO has a hierarchical set-up: Lower system levels, i.e., subfields, crop stands and products are regarded as elements of the higher system levels like crop rotation or farm. Interactions between different sectors of the farm and the relationships to the environment are depicted as mass and energy fluxes (see Figs. 1 and 2). REPRO has a modular set-up and comprises the following components:

- relational databases for the handling of site and management information,
- balancing models for the description of farm-specific mass and energy fluxes[13–15],
- empirical models, for example for the estimation of soil loss by water erosion[16] and for the assessment of soil compaction damage caused by machine passage[17],
- interfaces to C/N simulation models[18],
- interfaces to Geographic Information Systems[16],
- rating methods, for example for indicators and evaluation functions[12].

In the program, on-farm mass fluxes are described as closed cycles. The partial balances are interlocked, the outputs of one subsystem are the inputs of the other, as shown by the following example: the path of the produced feed is completely traced in quantity and quality from the field via preservation, storage and use down to the stable. Farm manure produced in dependence on feed input, animal performance and technological design is depicted both in quantity and quality from the very beginning via excreta storage to spreading it on the field. On-farm N transfers and N emissions are thoroughly considered by the program[13]. The objective to balance the C containing mass fluxes made it necessary to identify relevant C fluxes and C pools, to derive appropriate algorithms and model parameters using findings from the literature and our own research results, to design the software module and to link it with the already existing modules[13]. To balance the net greenhouse effect, the quantities of N_2O, CH_4 and CO_2 emissions are determined and evaluated. All emissions were converted to CO_2 equivalents [CO_2 eq] using their specific global warming potential (GWP), which determines the relative contribution of a gas to the greenhouse effect. The GWP index is defined as the cumulative radiative forcing between the present and a selected time in the future, caused by a unit mass of gas emitted now[19]. The GWP (with a time span of 100 years) of CO_2, CH_4 and N_2O is 1, 23 and 296, respectively.

In order to quantify the C fluxes, primarily the following approaches have been used.

Δ Soil organic carbon (Δ SOC). Changes in SOC were determined by use of humus balancing[12]. This method includes analyses of the crop-specific effects (depending on site, yield and mineral N doses) and of the organic fertilizers (depending on quantity and quality) on the humus level of the soil. The parameters were derived in long-term

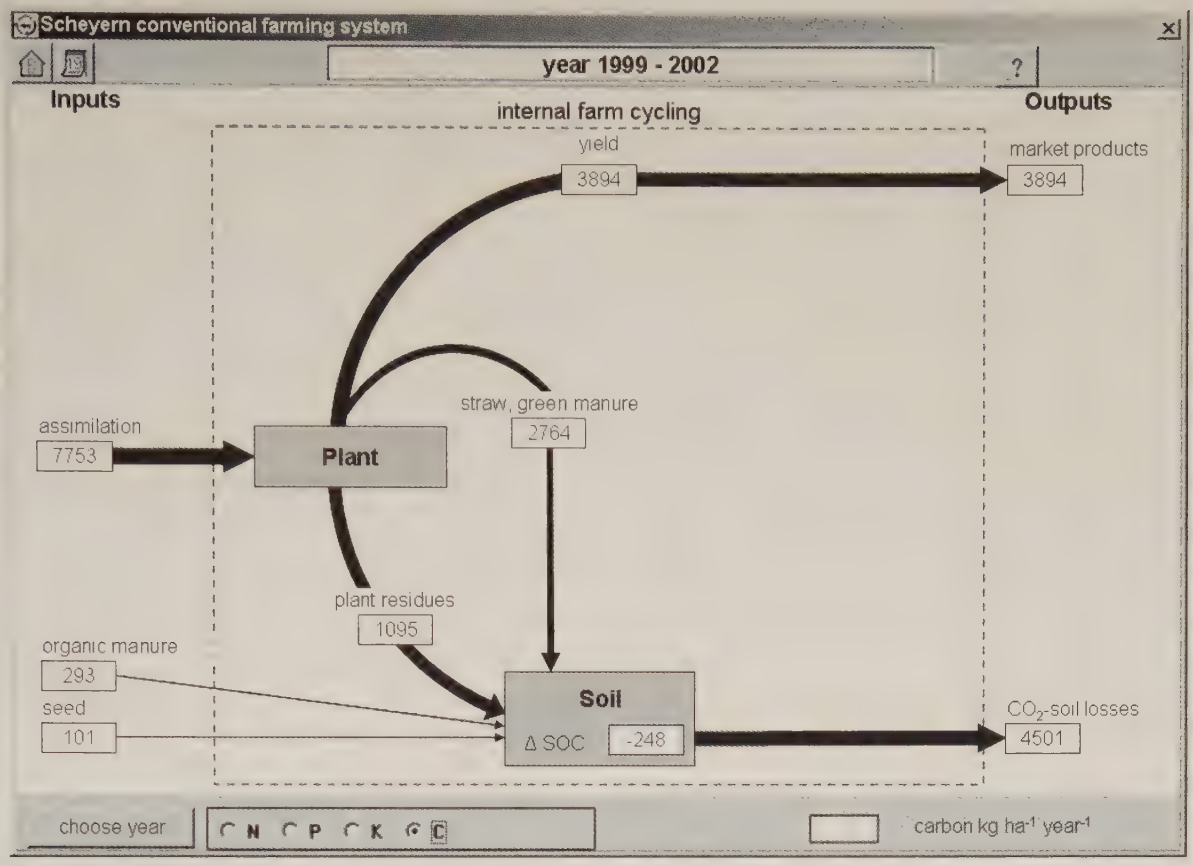

Figure 2. On-farm carbon cycle of the conventional farming system Scheyern, kg C ha^{-1} yr^{-1} (av. 1999–2002), screenshot of the model REPRO.

field experiments run with various crop rotations and fertilization patterns in regions of different soil and climate conditions, for example on diluvial, loess and highland sites, surveying the development of SOC over more than 20 years. Indirectly, the parameters also take into account root mass and rhizodeposition of the crops, as well as type and intensity of tillage. The mean crop-specific coefficients Δ SOC [Mg ha^{-1} yr^{-1}] are: potato, –1.0 to –1.6; maize, –0.7 to –1.2; winter wheat, –0.4 to –0.8; grass–clover–alfalfa (GCA), 0.9 to 1.2. The indicated variability ensues from the influence of factors such as yield (yield-related root mass and C input), production technology (e.g., effect of fertilization) and site conditions (e.g., soil texture). These factors do not include the effects of the byproducts (straw, beet tops, potato vines) and of mulched biomass (GCA) on SOC; they were determined on the basis of biomass input. The mean humus reproduction coefficients Δ SOC [kg C (kg C Input)$^{-1}$] are: farmyard manure (FYM), 0.35; slurry, 0.26; straw, 0.21 and green manure, 0.14. Slurry provides 75%, straw 60% and green manure 40% of the humus reproduction performance of FYM. The parameters were determined with regard to the C turnover in open field trials. Apart from this, analyses were also made of the C turnover of organic matter in incubation tests under controlled laboratory conditions[12,20,21].

C assimilation and C inputs to soils by plants. The net C assimilation of the plants was estimated from the measured aboveground net primary production (ANPP) and the C contents in the biomass. The harvested yield of the main products was entered as measured value. The soil C inputs were estimated as crop, yield and site specific values with consideration of: (1) byproducts, (2) crop residues (stubble), (3) roots and (4) rhizodeposition (exudates and root turnover in the growth period). The parameters were based on measurements in field experiments[22,23] and on data obtained in a literature study. By use of this method, the following values were obtained for winter wheat, for example: dry matter (DM) and C quantities [Mg ha^{-1} yr^{-1}]: grain as main product 5.0 Mg DM, 2.22 Mg C; straw as byproduct 4.0 Mg DM, 1.84 Mg C; stubble 0.8 Mg DM, 0.37 kg C; roots 1.3 Mg DM, 0.52 Mg C; rhizodeposition 0.8 Mg DM, 0.31 Mg C; total biomass 11.9 Mg DM, 5.26 Mg C. Thus, the C harvest index (harvested biomass [kg C ha^{-1}]/total biomass [kg C ha^{-1}]) amounted to 0.42 for mere grain harvesting and 0.77 when grain and straw were harvested as well.

CO_2 emissions from the use of fossil energy. CO_2 and energy balances are interlocked; they consider direct and indirect inputs of fossil energy and the involved CO_2 emissions. Energy balancing has been performed according to Hülsbergen et al.[10,15]. Energy inputs and CO_2 emissions have been estimated by use of the parameters listed in Tables 1 and 5; the determined energy outputs are based on the calorific values per kilogram DM as given in Table 3.

CH_4 emissions. The metabolic methane emissions from livestock keeping were estimated with regard to animal species, performance and feeding. On the basis of the feed gross energy, methane releases were estimated by means of conversion factors. For quantifying the methane release from organic fertilizer during storage, the excreta output (quantity, chemical components, degradability) was chosen as the basis for calculating the methane formation potential; the amount of produced methane was then determined with regard to the storage system[24].

N fluxes relevant for an emission inventory were estimated as follows:

N_2O emissions. N_2O emissions were estimated following the IPCC approach[24]. It was assumed, albeit very simplified, that 1.25% of the nitrogen supplied to the soils by organic and mineral fertilization, N_2 fixation and N deposition is emitted in the form of N_2O–N. Alternatively, a N_2O–N emission factor of 2.53% of the total N input as obtained in numerous measurements at the experimental farm[8] was applied. The indirect N_2O emissions from gaseous NH_3 and NO_x losses as well as from N losses via leaching were quantified using emission factors[24].

N_2 fixation. The symbiotic N_2 fixation by legumes has been estimated under the assumption that the fixation rate rises with increasing yields[12,25]. The yields were entered into the calculations in the form of measured values. For each legume crop a specific N_{dfa} value (N_{dfa} = nitrogen derived from atmosphere) was assumed which was modified according to the given conditions, among others the content of plant available nitrogen in the soil (i.e., GCA under organic conditions: $N_{dfa} = 0.90$, under conventional conditions: $N_{dfa} = 0.80$). The N quantities bound in roots, crop residues and rhizodeposition were estimated using crop specific parameters[12]. The legume share of the crop blends (mass %) was entered as measured or estimated value.

Experimental site and test farms

The described model was applied (1) in the experimental farm Scheyern located 40 km north of Munich in southern Germany (48°30.0′N, 11°20.7′E) and (2) in 28 commercial farms under comparable climate and soil conditions.

(1) In the experimental farm Scheyern, investigations of processes taking place in agroecosystems were made as well as analyses and optimization studies of the sustainability of management systems[11]. In 1992, the farm was divided into two independent farming systems with experimental character. One farm (31.5 ha arable land and 25.4 ha grassland) has been managed according to the principles of organic farming (org), the other (30.0 ha arable land) has remained under conventional management (con).

The research station is located 445–498 m above sea level, in a hilly landscape derived from tertiary sediments partly covered by loess. There is a high variability of soil types and soil properties; most soils have a loamy texture and are classified as Cambisols or Eutrochrepts. The mean annual precipitation is 833 mm, the mean annual temperature 7.4°C[11].

The productivity of the two farm sites is not absolutely the same. The organic farm works land of a slightly lower yield potential and steeper sloping than the conventional counterpart. The arable areas (AAs) of the organic farm scores 48, the conventional farm 52 points on an average (100 scores correspond to the highest cropping capacity according to German Soil Classification Scheme[26]). The organic farm keeps a suckler cowherd. The stock density had increased step by step from 0 LSU ha^{-1} (in 1992) to 1.4 LSU ha^{-1} (av. 1999–2002) and was then continuously reduced again (LSU = Livestock Unit according to FAO). Thus, different intensity levels and on-farm mass fluxes were reached. In compliance with the guidelines for organic farming, mineral N and chemico-synthetic plant protection products have been omitted. Since arable and grassland soils in both farms show high to very high nutrient levels, no mineral P and K doses needed to be applied in the reference period. The crop rotation of the organic system comprised: (1) GCA, (2) potatoes + undersown mustard, (3) winter wheat, (4) sunflower + undersown GCA, (5) GCA, (6) winter wheat, and (7) winter rye + undersown GCA.

The conventional farm has specialized on cash crop production. The crop rotation included: (1) potatoes + mustard as catch crop, (2) winter wheat, (3) maize + mustard as catch crop and (4) winter wheat. Occasionally, silage maize was sold to a neighboring farm for an equivalent import of cattle slurry. The organic crop rotation has a much broader crop diversity than the conventional. The mean size of a crop rotation field is 4.5 ha (org) and 7.5 ha (con).

Tillage was adjusted to the cropping systems. In the seven-field organic rotation, usually three operations with a moldboard plough are carried out and two with a chisel plough. In years of GCA cultivation, tillage is omitted. The conventional crop rotation refrains completely from ploughing.

The characterization of the systems according to tillage (org = with ploughing, con = no ploughing) reflects the practice in the commercial farms of the region. It becomes evident that the two management systems in Scheyern have very different structures and production features, but this is typical for the different farming systems (org and con) and also for the region. The farming systems of Scheyern have been subjected to numerous evaluations and comparisons of the effects of organic and conventional farming on the abiotic and biotic environment (among others[8,27–29]).

For more than 15 years an intensive monitoring program has been run on the farm areas. From the very beginning of the investigations, all operations have been documented in electronic field files.

Yields, DM and nutrient contents of the harvested products were documented on field and subfield level

Table 1. Mass and energy input in the organic farm Scheyern averaging the years 1999–2002.

Field	Crop[1] *+catch crop*[3]	N_2 fixation (kg ha^{-1})	Organic matter input			Energy input[2] (GJ ha^{-1})
			Type	N (kg ha^{-1})	C (kg ha^{-1})	
1	GCA	261				5.0
2	Potatoes		FYM	186	3099	10.5
			Residues[4]	31	1377	
	+undersown mustard		*Green manure*[4]	*46*	*851*	*1.1*
3	Winter wheat		FYM	99	1714	4.7
			Slurry	18	107	
4	Sunflower		FYM	82	1310	3.5
			Slurry	8	50	
			Straw[4]	39	1096	
	+undersown GCA	*31*	*Green manure*[4]	*46*	*808*	*1.5*
5	GCA	236				4.6
6	Winter wheat		FYM	26	477	4.9
			Slurry	23	139	
7	Winter rye		FYM	95	1625	4.3
			Slurry	17	102	
	+undersown GCA	*50*				*1.4*
	Crop rotation	**83**		**102**	**1822**	**5.9**
	Grassland	33	FYM	10	156	2.7
			Slurry	8	50	
			Excreta	87	890	
	Agricultural area (AA)	**60**		**104**	**1499**	**4.5**

[1] Crop rotation: (1) GCA (*Lolium perenne* L. + *Trifolium pratense* L. + *Medicago sativa* L.), (2) potatoes (*Solanum tuberosum* L.) + undersown mustard (*Sinapis alba* L.), (3) winter wheat (*Triticum aestivum* L.), (4) sunflower (*Helianthus annuus* L.) + undersown GCA, (5) GCA, (6) winter wheat, and (7) winter rye (*Secale cereale* L.) + undersown GCA.
[2] To calculate the energy input, the following energy equivalents per kilogram were assumed: diesel, 46.6 MJ; mineral N, 35.3 MJ; P fertilizer, 36.2 MJ; K fertilizer, 11.2 MJ; herbicides, 288 MJ; insecticides, 237 MJ; seed of winter wheat, 5.5 MJ; potato seed, 1.3 MJ; machines, 108 MJ[12,44].
[3] *All information on catch crops in italic.*
[4] Non-harvested plant biomass (potato vines, non-harvested biomass of mustard and GCA and sunflower straw). Stubble, roots and rhizodeposition are not included.

separately. Before spreading, the doses of farm manure were weighed and their nutrient contents determined in laboratory analyses. In 50 × 50 m grids, SOC, SON and nutrient levels have been sampled at time intervals of 5 years. The Ap-horizon revealed SOC levels of 1.39% (0.78–2.69, $n = 116$) in the organic and 1.25% (1.05–2.08, $n = 106$) in the conventional farm (sampling of 2001[30]). In some places, relevant C and N fluxes were measured, for example the N_2O emissions[8]. Thus, a rich data pool is now available which is used for the validation of the model software. As reference period the years 1999–2002 were chosen because during this time no management changes took place, and the systems had principally became established since the management shift in 1992.

(2) The 28 commercial farms are located in the surroundings of the experimental farm Scheyern (mean distance 60 km). Of the monitored farms, 18 are run organically (org), 10 conventionally (con). The soils are similar to those in Scheyern; their mean yield productivity, however, ranks slightly higher in view of scores average of 58 (40–70) (org) and 61 (45–77) (con). The livestock density is 0.5 (0.0–1.4) LSU ha^{-1} (org) and 0.8 (0.0–2.2) LSU ha^{-1} (con). The crop rotations vary broadly. The proportion of grain crops amounts to 60 (35–80)% of the AA (org) and 70 (50–80)% (con), respectively. Legumes occupy 25 (15–45)% (org) and 5 (0–20)% (con) of the AA, row crops 3 (0–25)% (org) and 15 (0–50)% (con), respectively.

Results

Experimental farm Scheyern

Mass and energy inputs in the cropping system. At a N_2 fixation rate of 83 kg ha^{-1} yr^{-1} (Table 1), the organic crop rotation is based on legumes. Due to a stock density of 1.4 LSU ha^{-1}, large C and N quantities circulate at farm level. For each hectare of arable land, 70 kg N bound in FYM and 9 kg N bound in slurry are available. The residues of sunflower and potatoes, non-harvested GCA and the residues of the cover crop (mustard) are usually incorporated into the soil. The straw of the small grain crops is used as bedding material and returns to the land as FYM. The C/N ratio of the organic matter supplied to the soil in the organic system is 18 : 1 on

Table 2. Mass and energy input in the conventional farm Scheyern averaging the years 1999–2002.

Field	Crop[1] +*catch crop*[3]	Mineral N (kg ha^{-1})	Organic matter input			Energy input[2] (GJ ha^{-1})
			Type	N (kg ha^{-1})	C (kg ha^{-1})	
1	Potatoes	90	Residues[4]	75	2495	16.1
	+catch crop mustard	*20*	*Green manure*[4]	*127*	*2011*	*2.0*
2	Winter wheat	160	Slurry	46	360	11.6
			Straw[4]	28	2182	
3	Maize	130	Slurry	21	215	12.5
	+catch crop mustard	*20*	*Slurry*	*37*	*390*	
			Green manure[4]	*127*	*2011*	*2.0*
4	Winter wheat	160	Slurry	28	208	11.6
			Straw[4]	30	2355	
	Crop rotation	**145**		**130**	**3057**	**14.0**

[1] Crop rotation: (1) potatoes + mustard as catch crop, (2) winter wheat, (3) maize (*Zea mays* L.) + mustard as catch crop, (4) winter wheat.
[2] Energy equivalents: see Table 1.
[3] *All information on catch crops in italic.*
[4] Non-harvested plant biomass (potato vines, non-harvested biomass of mustard and cereal straw). Stubble, roots and rhizodeposition are not included.

an average (FYM 17 : 1, slurry 6 : 1 and residues 24 : 1–30 : 1). The nitrogen returns mainly as organically fixed N; the NH_4–N proportion in FYM amounts to 25%.

From the energetic point of view, the organic crop rotation is run as a low-input system with 5.9 GJ ha^{-1} yr^{-1}; only potato cropping requires higher energy inputs (10.5 GJ ha^{-1} yr^{-1}) compared to cereals. This has to be attributed to the labor-intensive planting, cultivation and harvesting of potatoes. The grassland area is under extensive use (energy input 2.7 GJ ha^{-1}).

The conventional farm is oriented on mineral nitrogen (Table 2); the N doses (145 kg ha^{-1} yr^{-1}) are typical for the region. Although the farm has specialized on cash crops, over the whole crop rotation period more C and N are returned in organic form than in the stocked organic system. The reasons are: large quantities of straw remaining on the land for shallow incorporation and also large amounts of cover crop residues, due to favorable growth conditions. The mean C/N ratio of the supplied organic matter is relatively high (24 : 1) owing to the big share of straw (slurry 6 : 1, wheat straw and maize residues 80 : 1, residues of cover crops and potatoes 27 : 1).

In view of the energy input of 14 GJ ha^{-1} yr^{-1}, the system is run on a high-input level.

Production performance and efficiency levels in the cropping system. Depending on the type of management, yields are clearly differentiated. Potatoes and winter wheat are grown in both crop rotations; a juxtaposition of the yield productivity of these crops underlines the higher yield level under conventional management (Tables 3 and 4). In the organic crop rotation, the recorded 8.3 Mg ha^{-1} yr^{-1} corresponds to about 57% of the conventional DM yield, 163 kg N ha^{-1} yr^{-1} equal to about 66% of the N removal, and 3741 kg C ha^{-1} yr^{-1} to roughly 56% of the C bound in the conventional rotation (Tables 3 and 4).

The N surplus (N input minus N removal) amounts to 22 kg ha^{-1} yr^{-1} (org) versus 28 kg ha^{-1} yr^{-1} (con). Considering the measured N emissions of 16 kg ha^{-1} yr^{-1} and the calculated changes of 35 kg ha^{-1} yr^{-1} (org) and –24 kg ha^{-1} yr^{-1} (con) in the soil N reserves due to changes in humus level (Tables 5 and 6), N surplus figures have to be adjusted to 3 kg ha^{-1} yr^{-1} (org) and 68 kg ha^{-1} yr^{-1} (con), respectively. This reveals higher N loss potentials in the conventional system.

The energy output/input ratio displays clear differences in the energy efficiency of crops and crop rotations. By far the highest energy efficiency is reached in GCA cropping due to low inputs (no fertilizer application), but high energy binding in the harvested biomass. Averaging the organic crop rotation, 18 GJ are bound per GJ of supplied energy; this value ranks about 60% above that of the conventional farm. If the straw harvested in the organic farm were evaluated in an energy balance sheet, the energy output/input ratio would rise to at least 21. Interpreting this value, it must be underlined that the harvested straw is destined only for animal bedding without any utilization in feeding or as energy source.

On-farm C cycles. Depending on the farm structure, mass fluxes in both systems are basically different; the organic system is oriented on closed cycles, the conventional counterpart on transitional fluxes (Figs. 1 and 2). The organic farm imports considerable forage quantities from adjacent organic areas, thus supporting its C fluxes.

The C assimilation efficiency of the organic farm reaches nearly 70% of that of the conventional farm, because GCA and grassland leave a large root mass in the soil. In the organic system, the C input with crop and root residues is 80% higher than in the conventional variant. On the other hand, extremely large C quantities are supplied to the soils of the conventional farm as straw and green biomass, which raises the total C input in the conventional system to 4253 kg ha^{-1} yr^{-1} and exceeds the C supply to the organic system (3497 kg ha^{-1} yr^{-1}). Depending on the different humus replacement potential of FYM and slurry compared

Table 3. ANPP and energy efficiency in the organic farm Scheyern averaging the years 1999–2002.

Field	Crop +*catch crop*[1]	ANPP Type	DM (Mg ha^{-1})	N (kg ha^{-1})	C (kg ha^{-1})	GJ[2] (ha^{-1})	Energy output/input ratio[4]
1	GCA	Forage	11.8	304	5335	213	42.6
2	Potatoes	Tubers	4.9	66	2044	84	8.0
		Green manure	3.4	31	1377	59	
	+undersown mustard	*Green manure*	*1.9*	*46*	*851*	*32*	
3	Winter wheat	Grain	2.4	49	1110	45	9.6
		Straw	2.2	10	1016	39	
4	Sunflower	Grain	1.6	46	864	43	12.2
		Straw	2.4	39	1096	43	
	+undersown GCA	*Green manure*	*1.8*	*46*	*808*	*32*	
5	GCA	Forage	10.9	283	4942	197	42.8
6	Winter wheat	Grain	3.1	69	1403	58	11.9
		Straw	2.8	13	1320	50	
7	Winter rye	Grain	2.9	48	1317	54	12.6
		Straw	2.9	16	1365	53	
	+undersown GCA	*Forage*	*2.9*	*76*	*1339*	*53*	*37.9*
	Crop rotation		**8.3**	**163**	**3741**	**107**[3]	**18.0**
	Grassland	Forage	6.2	136	2819	111	41.1
	Agricultural area		**7.3**	**151**	**3330**	**109**[3]	**28.3**

[1] *All information on catch crops in italic.*
[2] To calculate the energy recovery in ANPP, the following calorific values per kg DM were assumed: potato tubers, 17.2 MJ; potato vines, 17.0 MJ; winter wheat grain, 18.6 MJ; winter wheat straw, 17.7 MJ; winter rye grain, 18.3 MJ; winter rye straw, 18.3 MJ; GCA, 18.1 MJ; sunflower grain, 26.8 MJ; sunflower straw, 18.0 MJ; mustard, 16.6 MJ[10].
[3] Energy recovery in ANPP of the main products (without byproducts and non-harvested biomass).
[4] Energy output/input ratio = energy recovery in ANPP of the main products/energy input.

Table 4. ANPP and energy efficiency in the conventional farm Scheyern averaging the years 1999–2002.

Field	Crop +*catch crop*[1]	ANPP	DM (Mg ha^{-1})	N (kg ha^{-1})	C (kg ha^{-1})	GJ[2] (ha^{-1})	Energy output/input ratio[4]
1	Potatoes	Tubers	8.9	128	3695	153	9.5
		Green manure	6.2	75	2495	106	
	+catch crop mustard	*Green manure*	*4.2*	*127*	*2011*	*71*	
2	Winter wheat	Grain	5.9	144	2760	110	9.5
		Straw	4.7	28	2182	84	
3	Maize	Silage	13.8	178	6204	255	20.4
	+catch crop mustard	*Green manure*	*4.2*	*127*	*2011*	*71*	
4	Winter wheat	Grain	5.5	149	2917	103	8.9
		Straw	4.4	30	2355	78	
	Crop rotation		**14.5**	**247**	**6658**	**155**[3]	**11.1**

[1] *All information on catch crops in italic.*
[2] Calorific values: see Table 3.
[3] Energy recovery in ANPP of the main products (without byproducts and non-harvested biomass).
[4] Energy output/input ratio = energy recovery in ANPP of the main products/energy input.

to straw and the humus accumulation by GCA, a rise in the SOC was estimated for the AA of the organic system and a decline for the conventional system. A C steady state (Δ SOC = 0) has been assumed for the grassland during the regarded period, because it represents permanent grassland without any changes in management.

By way of computing, the soil-borne CO_2 respiration ($= \Sigma\Delta$ C input $- \Delta$ SOC) turned out to be 3293 kg ha^{-1} yr^{-1} (org) and 4501 kg ha^{-1} yr^{-1} (con) (Figs. 1 and 2).

The differing yield levels, but mainly the different use of the products, produce substantial variations in the C output. In the cash crops, 342 kg ha^{-1} yr^{-1} (org) and 3894 kg ha^{-1} yr^{-1} (con), respectively, are fixed. The C quantities in animal products amount to 127 kg ha^{-1} yr^{-1} (org). The stock-keeping organic farm involves C loss processes that do not take place in the cash crop farm, for example metabolic CH_4 (109 kg C ha^{-1} yr^{-1}) and CO_2 emissions from the animals (1300 kg C ha^{-1} yr^{-1}) as well

Table 5. Annual C sequestration and estimated emissions of greenhouse gases in the organic farm Scheyern averaging the years 1999–2002.

		C sequestration in SOM			Fertilizer	Fuel	Pesticides	Machines	N_2O	Net GGE[5–7]
Field	Crop *+catch crop*[1]	Δ C, Crop[2] (kg ha^{-1})	Δ C, Manure[3] (kg ha^{-1})	CO_2 eq (kg ha^{-1})	CO_2 eq (kg ha^{-1})	CO_2 eq (kg ha^{-1})	CO_2 eq (kg ha^{-1})	CO_2 eq (kg ha^{-1})	CO_2 eq (kg ha^{-1})	CO_2 eq (kg ha^{-1})
1	GCA	916	0	−3362	0	345	0	121	1733	−1203
2	Potatoes	−1073	1259	−681	0	366	62	352	1358	1417
	+undersown mustard	*110*	*110*	*−808*	*0*	*94*	*0*	*9*	*247*	*−471*
3	Winter wheat	−626	696	−255	0	213	0	168	782	869
4	Sunflower	−719	412	1128	0	204	0	145	602	2039
	+undersown GCA	*307*	*516*	*−3022*	*0*	*92*	*0*	*11*	*683*	*−2277*
5	GCA	945	0	−3470	0	316	0	114	1644	−1436
6	Winter wheat	−806	191	2256	0	252	0	153	375	2996
7	Winter rye	−650	592	213	0	225	0	177	720	1295
	+undersown GCA	*394*	*0*	*−1447*	*0*	*95*	*0*	*9*	*416*	*−967*
	Crop rotation	**−172**[4]	**539**[4]	**−1350**	**0**	**315**	**9**	**180**	**1227**	**323**
	Grassland	0	0	0	0	195	0	55	813	1023
	Agricultural area	**−95**	**299**	**−748**	**0**	**261**	**5**	**124**	**1042**	**635**

[1] *All information on catch crops in italic.*

[2] C sequestration, net effect of the grown crop on SOC, caused by C inputs (stubble, roots, C rhizodeposition), influence on C mineralization and C immobilization, including the effects of the production technology (i.e.. type and intensity of tillage), computed with humus balancing. Negative values indicate a SOC decrease, positive values a SOC increase.

[3] C sequestration, net effect of the applied fertilizer (FYM and slurry) and the supply of plant biomass to the soil (straw, residues, non-harvested biomass of mustard and GCA) on SOC, with consideration of the specific humus replacement rate (see Methods and Materials), computed with humus balancing.

[4] Averaging the crop rotation, C sequestration amounts to 367 (539–172) kg C ha^{-1} yr^{-1}, this equals a N immobilization in SOM of 35 kg N ha^{-1} yr^{-1} at a C/N-ratio of 10.5:1 in SOM.

[5] To calculate the GGEs, the following CO_2 emissions per kilogram were assumed: diesel, 4.19 kg; mineral N, 2.86 kg; P fertilizer, 2.57 kg; K fertilizer, 0.73 kg; herbicides, 23.10 kg; insecticides, 23.10 kg; seed of winter wheat, 0.55 kg; potato seed, 0.13 kg; machines, 4.71 kg[44].

[6] Plus denotes an increase, minus a reduction in net GGEs.

[7] To calculate the net GGEs, a methane uptake by the soil of 40 kg CO_2 eq ha^{-1} yr^{-1} is considered.

Table 6. Annual C sequestration and estimated emissions of greenhouse gases in the conventional farm Scheyern averaging the years 1999–2002.

Field	Crop +*catch crop*[1]	C sequestration in SOM			Fertilizer	Fuel	Pesticides	Machines	N_2O	Net GGE[5–7]
		Δ C, crop[2] (kg ha^{-1})	Δ C, manure[3] (kg ha^{-1})	CO_2 eq (kg ha^{-1})	CO_2 eq (kg ha^{-1})	CO_2 eq (kg ha^{-1})	CO_2 eq (kg ha^{-1})	CO_2 eq (kg ha^{-1})	CO_2 eq (kg ha^{-1})	CO_2 eq (kg ha^{-1})
1	Potatoes	−1230	296	3426	254	352	341	268	1115	5717
	+*catch crop mustard*	*116*	*261*	*−1384*	*61*	*250*	*34*	*55*	*853*	*−170*
2	Winter wheat	−563	545	64	467	220	132	132	1422	2397
3	Maize	−795	70	2661	481	268	84	136	947	4537
	+*catch crop mustard*	*116*	*261*	*−1384*	*61*	*250*	*34*	*55*	*853*	*−170*
4	Winter wheat	−603	534	255	462	217	139	128	1317	2479
	Crop rotation	**−740**[4]	**492**[4]	**910**	**446**	**389**	**191**	**194**	**1627**	**3697**

[1] *All information on catch crops in italic.*
[2,3] Estimation of C sequestration see Table 5.
[4] Averaging the crop rotation, C sequestration was –248 (492–740) kg C ha^{-1} yr^{-1}, this equals to a N immobilization in SOM of –24 kg N ha^{-1} yr^{-1} at a C/N-ratio of 10.5 : 1 in SOM.
[5] Calculation of the GGEs see Table 5.
[6] Plus denotes an increase, minus a reduction in net GGEs.
[7] To calculate the net GGEs, a methane uptake by the soil of 40 kg CO_2 eq ha^{-1} yr^{-1} is considered.

as losses from farm manure on store (Fig. 1). Due to their high specific GWP, CH_4 emissions have a particular importance.

Inventory of climate relevant gases. The inventory of climate relevant gases (Tables 5 and 6) includes exclusively the cropping sector and allows comparisons of the systems on the levels arable land, crop rotation and crop species. Emissions from the livestock sector were not considered.

The results elucidate the influence of crops and fertilization (Δ SOC), cropping intensity (energy input) and crop rotation pattern on the emission of greenhouse gases. The biggest influence on the greenhouse effect is exerted by the Δ SOC and N_2O emissions. The GGEs [CO_2 eq] caused by fuel input (org: 315 kg ha^{-1} yr^{-1} and con: 389 kg ha^{-1} yr^{-1}) and the manufacture of the machines (org: 180 kg ha^{-1} yr^{-1} and con: 194 kg ha^{-1} yr^{-1}) are equally high in both crop rotations. More intensive tillage, manure spreading operations and more field passages for mechanical crop cultivation in the organic farm are compensated in the conventional farm by operations for spreading mineral fertilizer and pesticides and also by a higher input for harvesting the larger biomass yields. As a result of mineral N and pesticide applications, additional 637 kg ha^{-1} yr^{-1} CO_2 eq from the upstream sector are emitted in the conventional system.

Pertaining to the mitigation of GGEs, the most favorable effect among the crops with a negative greenhouse effect is reached by GCA, owing to C sequestration in the range of about 0.9 Mg ha^{-1} yr^{-1}. High GGE values were obtained for the row crops potato and maize, favorable levels for catch crops. Related to the cultivated area, the organic rotation produces only 10% of the greenhouse effect of the conventional rotation; related to the energy fixed in the harvested products, approximately 18%.

Results of 28 farms in the region

The mean energy input in the organic farms amounts to 5.3 GJ ha^{-1} yr^{-1} (Table 7) which corresponds to the situation in the organic farm in Scheyern. Due to differences in cropping structures and management, some farms rank above this level by up to 50%. The application of mineral fertilizers and chemical plant protection involves clearly higher energy inputs in the conventional farms (11.7 GJ ha^{-1} yr^{-1}). Within the range of fluctuation (9.5–15.0 GJ ha^{-1} yr^{-1}), only one farm exceeded the cropping intensity of the conventional system in Scheyern (14.0 GJ ha^{-1} yr^{-1}).

In the organic farms DM yields (2.0–7.7 Mg ha^{-1} yr^{-1}) vary much more than in the conventional farms (4.5–9.0 Mg ha^{-1} yr^{-1}). The highest-yielding organic farms reach the mean yield level of the conventional farms. The DM yields are not only conditioned by the management system (org versus con) but also by the disposal of the grown biomass. High DM yields were recorded mainly in connection with a high harvest index (i.e., use of byproducts and catch crops). The energy efficiency,

Table 7. Coefficients of mass and energy budget, C sequestration and estimated GGEs in the monitored farms, averaging the arable land.

		Organic farms (18+1)				Conventional farms (10+1)			
Parameter	**Unit**	**Scheyern**	**Medium**	**Min**	**Max**	**Scheyern**	**Medium**	**Min**	**Max**
Energy input[1]	GJ ha^{-1}	5.9	5.3	4.1	7.8	14.0	11.7	9.5	15.0
N input[2]	kg N ha^{-1}	204	152	108	227	296	246	193	304
DM yield	Mg ha^{-1}	5.8	3.8	2.0	7.7	8.5	7.6	4.5	9.0
Energy output/input ratio		18.0	13.0	6.0	19.3	11.1	11.8	6.1	16.2
C sequestration[3]	CO_2 eq kg ha^{-1}	−1350	−452	−1830	489	910	266	−659	910
N_2O emissions	CO_2 eq kg ha^{-1}	1227	887	631	1322	1627	1418	1123	1771
Emissions from fossil energy input	CO_2 eq kg ha^{-1}	504	454	320	750	1220	1037	819	1220
Net GGE[4,5]	CO_2 eq kg ha^{-1}	323	887	106	1875	3697	2717	1878	3697
Net GGE winter wheat[5]	CO_2 eq kg ha^{-1}	1968	1669	−278	2966	2514	2333	1478	3680
Net GGE[6]	CO_2 eq kg Mg^{-1}	56	263	23	431	434	376	271	434
Net GGE winter wheat[6]	CO_2 eq kg Mg^{-1}	715	496	−102	958	441	355	213	545

[1] Energy equivalents: see Table 1.
[2] N input = sum of N emissions (16 kg ha^{-1} yr^{-1}), N_2 fixation, organic and mineral fertilizer and non-harvested residues.
[3] Plus denotes mineralization and loss of SOC to the atmosphere, minus denotes an immobilization and sequestration of C in the soil.
[4] Plus denotes an increase, minus a reduction in net GGEs.
[5] Area-related calculation of the GGEs.
[6] Product-related calculation of the GGEs.

expressed as energy output/input ratio, is on the same level in organic and conventional farms.

The calculated C sequestration [CO_2 eq] varies broadly both in organic and conventional farms. Averaging all organic farms, C sequestration amounts to (+123 kg C ha^{-1} yr^{-1} = reduction of the greenhouse effect by 452 kg CO_2 eq ha^{-1} yr^{-1}), while the conventional farms reveal depleting SOC levels (−73 kg C ha^{-1} yr^{-1}, with an increase of the greenhouse effect by 266 kg CO_2 eq ha^{-1} yr^{-1}). The deviating development of the SOC stock is caused by different crop rotations (high legume proportion (org) versus high proportion of cereals and row crops (con)) and by the quantity and quality of the organic matter supplied to the soil (mainly FYM (org) versus straw and slurry input (con)).

In view of lower N and energy inputs in the organic farms, their N_2O and CO_2 emissions are clearly lower. The area-related total GGEs from the conventional farms (2717 kg CO_2 eq ha^{-1} yr^{-1}) with consideration of SOC changes are nearly threefold higher than the GGE from the organic farms (887 kg CO_2 eq ha^{-1} yr^{-1}).

The differences are lower when we regard the single crop species. Winter wheat is directly comparable because of its major position in the cropping structure of both farming systems (org and con). Regarding the 1669 kg CO_2 eq ha^{-1} averaging all organic farms, we come to 72% of the emissions from conventional systems. When we focus on the harvested product [per Mg DM], lower yields in organic farming involve higher emissions (496 kg CO_2 eq Mg^{-1} (org) and 355 kg CO_2 eq Mg^{-1} con). When all products [Mg DM] of the analyzed crop rotation are taken into account, organic management produced emissions of 263 kg CO_2 eq Mg^{-1}, for the conventional management 376 kg CO_2 eq Mg^{-1} were computed.

Breaking down the farms according to their stock density, the following emissions were computed (in kg CO_2 eq ha^{-1} yr^{-1}):

- organic farms keeping livestock: 851 kg CO_2 eq (thereof emissions from fossil energy input, 523 kg CO_2 eq; C sequestration, −658 kg CO_2 eq; N_2O emissions, 986 kg CO_2 eq):
- organic farms without livestock: 936 kg CO_2 eq (thereof emissions from fossil energy input, 359 kg CO_2 eq; C sequestration, −167 kg CO_2 eq; N_2O emissions, 744 kg CO_2 eq),
- conventional farms with livestock: 2531 kg CO_2 eq (thereof emissions from fossil energy input, 990 kg CO_2 eq; C sequestration, 64 kg CO_2 eq; N_2O emissions, 1477 kg CO_2 eq),
- conventional farms without livestock: 2939 kg CO_2 eq (thereof emissions from fossil energy input, 1093 kg CO_2 eq; C sequestration, 510 kg CO_2 eq; N_2O emissions, 1336 kg CO_2 eq).

Stocked farms reach higher C sequestration values due to the benefits of crop rotation (more forage cropping) and the effects of organic fertilizer. There is a tendency to increased N_2O emissions in stocked farms caused by higher N inputs with manure and legume fodder crops. Organic farms with stock require higher energy inputs connected with increased C emission due to additional harvesting and transport operations for forage provision. In principal it can be stated that the basic system-related differences in the emission potentials between organic and conventional farms continue to exist also, when we distinguish between stocked and stockless systems.

Relationship between energy input and GWP. The parameters energy input and net greenhouse effect in the

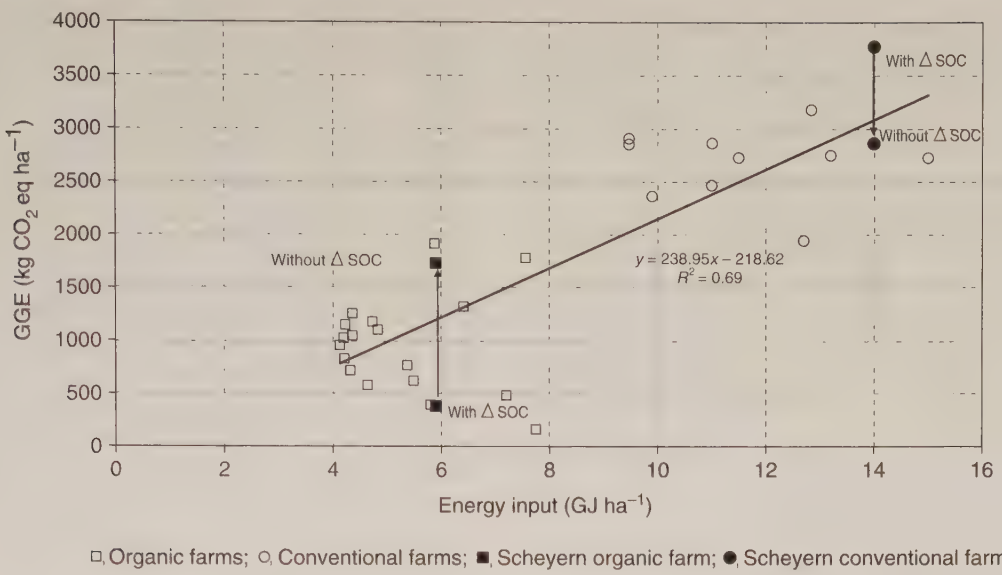
GGE (kg CO2 eq ha−1)
Energy input (GJ ha−1)
With Δ SOC
Without Δ SOC
Without Δ SOC
With Δ SOC
y = 238.95x − 218.62
R2 = 0.69
□, Organic farms; ○, Conventional farms; ■, Scheyern organic farm; ●, Scheyern conventional farm

Figure 3. Energy input and GGE, kg CO_2 eq ha^{-1} of the arable area in the organic and conventional farm in Scheyern and in the analyzed organic ($n = 18$) and conventional ($n = 10$) commercial farms.

experimental farm Scheyern and in the analyzed commercial farms ($n = 28+2$) have been compared in Figure 3. When all test farms are regarded as a basic population, a linear relationship is recorded between energy input and net greenhouse effect ($r^2 = 0.69$). Emissions rise with increasing input of fuel, fertilizer, pesticides and machines and the involved energy consumption.

Distinguishing between organic and conventional farms produces two clusters and a possible distinction between low and high-input systems. The organic farms are characterized by low energy inputs (4.1–7.8 GJ ha^{-1} yr^{-1}) and low GGE values (106–1875 kg CO_2 eq ha^{-1} yr^{-1}). They are in contrast with the conventional farms and their principally higher energy inputs (9.5–15.0 GJ ha^{-1} yr^{-1}) and higher GGE values (1878–3697 kg CO_2 eq ha^{-1} yr^{-1}). The relationship between energy input and greenhouse effect appears to be fuzzy because it has been affected by Δ SOC and N_2O emissions. Supposing the Δ SOC of the experimental farm Scheyern were not considered, the net greenhouse effect of the organic rotation would rise markedly, while that of the conventional rotation would decrease (Fig. 3).

Discussion

While sophisticated software programs for the analysis of nitrogen and energy fluxes at the farm level have been developed (e.g.[14,31–33]), few tools are available for the balancing of carbon fluxes in the system soil–plant–animal–environment. In the literature, various models have been described for the estimation of relevant CO_2, CH_4 and N_2O sources and sinks. There exist, for example, economic models with linear programming supplemented by algorithms for the estimation of the GWP of farms[34,35]. However, they do not link technical and biological C fluxes. The model REPRO is oriented on the description of such on-farm C fluxes; it combines the balancing of C, N and energy fluxes. A guiding principle during the development of the model was the depiction of farms as systems (Figs. 1 and 2). This distinguishes REPRO from other approaches. Analyses of farm enterprises on the basis of REPRO have shown that the analysed mass cycles depend on site conditions (soil and climate), farm structure (livestock density and crop rotation), inputs (fertilizers, pesticides and energy), outputs (plant and animal products for market presentation), cropping technologies (tillage and harvest procedure) and also on the interactions between these factors (see[12,14]). The relationships between management, C cycles and emission potentials have been demonstrated in detail in the example of the experimental farm Scheyern. Scheyern was divided into two independent farming systems with highly different mass fluxes despite comparable site conditions. The organic farm is characterized by a high crop diversity. The multiple, legume-based rotation favors high N_2 fixation rates; high stock numbers allow an intensive recycling of the organic matter, mainly by recirculating high-quality fertilizers in the form of FYM. The mass fluxes in the farm are oriented on closed matter cycles, from the energetic point of view the system is run on a low-input basis. Thus, Scheyern largely fulfills a basic criterion of organic farming: a principally closed mass cycle in a multi-structured farm. Only the relatively high feed extra-purchase and the involved C and N imports intensify the farm-internal mass fluxes decisively, thus restricting nutrient self-sufficiency. The conventional farm in Scheyern represents a very simply structured cash crop system with a crop rotation of low diversity. The farm is based on mineral nitrogen with transit character, from the energetic point of view a high-input system.

A rich database is available for the experimental farm. Part of the measured values, for example yields and nutrient

contents, were used in the model calculations. Other data, for instance emission and SOC measurements, are useful for the verification of the computed results.

The cropping systems in Scheyern have differentiated effects on SOC. For the years 1999–2002, the calculated mean C sequestration was 0.37 Mg ha^{-1} (org) and –0.25 Mg ha^{-1} (con), respectively (Tables 5 and 6). The levels determined for 1991–2001 are lower: 0.16 Mg ha^{-1} yr^{-1} (org) and –0.08 Mg ha^{-1} yr^{-1} (con), due to lower livestock density, lower use intensity in the early 90s and a modified crop rotation.

The chemico-analytical determination of SOC after 10 years of differentiated land use (1991–2001) revealed a SOC increase by 0.18 Mg ha^{-1} yr^{-1} (org; $n = 106$) and a SOC decrease by 0.12 Mg ha^{-1} yr^{-1} (con; $n = 116$), respectively[30]. It becomes obvious that measured and computed results are in good agreement. For a final evaluation, however, a longer period of monitoring will be necessary (see[36]).

C sequestration in the soil is often more influenced by the quality of the organic primary matter (probably because organic matter and residues with close C/N ratio are already partly decomposed and contain an increased proportion of chemically recalcitrant organic compounds) than by the quantity of the supplied matter (see[37]); this has to be taken into account when C cycles are to be described.

In Scheyern, SOC values increased under organic and declined under conventional farming, although the conventional crop rotation is a reduced-till system with higher C inputs. According to the humus balance, C sequestration relies strongly on the quality of the organic fertilizer (FYM versus straw) as well as on the legume share in the rotation. For GCA, C sequestration turned out to be 0.93 Mg ha^{-1} yr^{-1}; for maize (−0.72 Mg ha^{-1} yr^{-1}) and potatoes (−0.93 Mg ha^{-1} yr^{-1}; con) negative effects on SOC were computed. In Scheyern, only the overall influence of a cropping system on the SOC can be measured and not the separate effects by crops and fertilization measures. This would require a different approach, for example factorial field experiments. Experiments on C sequestration by perennial legumes, however, were already described in detail in literature and confirm the values communicated here. For example, the C sequestration rate of alfalfa obtained in field experiments under different climatic and soil conditions was reported to be 0.5 to >1.0 Mg ha^{-1} yr^{-1} ([3,4,12,38]).

In the present paper, the net greenhouse effect has been estimated with regard to the C sequestration. It should be pointed out that C accumulation and depletion as induced by management shifts are temporarily limited, and that with the development of new steady states Δ SOC finally falls to zero[39]. In view of this situation (Δ SOC = 0), the GGEs [CO_2 eq] in Scheyern reached 1673 kg ha^{-1} yr^{-1} (org) versus 2787 kg ha^{-1} yr^{-1} (con), which is clearly different from Tables 5 and 6. According to these findings, in the organic crop rotation about 60% of the GGEs from the conventional rotation are area-related and >100% product-related.

The N_2O emissions were quantified following IPCC[19]. To simplify the calculation it was assumed that 0.0125 kg N_2O–N kg^{-1} N input (deposition, mineral N, organic N and symbiotic N_2 fixation) is emitted. In recent publications, this relationship between N input and N_2O emission was principally confirmed. Petersen et al.[40] found an emission factor of 0.016 kg N_2O–N kg^{-1} N input ($r^2 = 0.56$) in European crop rotations, Gregorich et al.[41] reported for Canadian conditions 0.012 kg N_2O–N kg^{-1} N input ($r^2 = 0.43$).

Long-term measurements in Scheyern revealed that the IPCC method may lead to an underestimation of N_2O emissions (Tables 5 and 6)[8]. The N_2O emissions [kg N_2O–N ha^{-1} yr^{-1}] computed by us per hectare and year amounted to 0.8–3.1 kg for winter wheat, 2.4–2.9 kg for potatoes; the measured values were 1.8–16.8 kg for winter wheat and 5.3–8.2 kg for potatoes. Some N_2O measurement series in Scheyern, for example in wheat[42], furnished N_2O emission levels in the order of IPCC values; other measurements like those in potatoes[42] ranked clearly above the computed levels. It turned out that in potato crops very high N_2O quantities were emitted from the inter-ridge space[42]. According to Flessa et al.[8], the high N_2O emissions in Scheyern may probably be attributed to the local soil properties (high soil bulk density and soil water content, low O_2 availability) and the climatic conditions favoring denitrification. Also, increased emissions induced by freezing and thawing events occurred each year and accounted for a substantial part (30–50%) of the annual emissions[8,42].

The N_2O measurement series made in Scheyern shows that it is principally extremely difficult to project selective and temporarily limited measurements to large areas or even whole farms. Unfortunately, a generally applicable algorithm that considers, beside N inputs, other influential parameters like site conditions, crop species, tillage and soil N turnover, could not yet be derived from the values measured in Scheyern. Tools for a more precise estimation of emissions are simulation models, for example the software DNDC[43]. Currently, this software is in validation using N_2O measurement data from Scheyern.

Supposing a higher N_2O–N emission factor (2.53% of the total N input according to Flessa et al.[8], instead of 1.25% as calculated by IPCC[24]) is assumed, the emission inventory would be modified as follows: The GGEs [CO_2 eq] resulting from N_2O would rise from 1227 to 2483 kg ha^{-1} yr^{-1} (org) and from 1627 to 3294 kg ha^{-1} yr^{-1} (con), respectively; the total GGEs from both crop rotations would increase to 1579 kg ha^{-1} yr^{-1} (org) and 5363 kg ha^{-1} yr^{-1} (con). Accordingly, the organic rotation would reach 30% of the net greenhouse effect recorded in the conventional rotation.

The application of the model REPRO in 28 farms in southern Germany (Tables 7 and Fig. 3) revealed, under the given local conditions, distinct differences between organic and conventional farms concerning their structure, mass and energy inputs, yields, C sequestration and GGEs. From the energetic point of view, the organic farms are low-input, the conventional farms high-input systems. The

energy input is primarily related to the mineral N input. Increasing mineral N and energy inputs enhance also the area-related N_2O and CO_2 emissions; there is a linear relationship between energy input and GGEs per hectare (Fig. 3). Further factors are integrated in the computing of net GGEs like C sequestration, symbiotic N_2 fixation, energy input by the use of machines and fuel. This explains the enormous variability of the net greenhouse effect in organic and conventional farms (Fig. 3).

Our investigations have revealed that organic farms produce less area-related GGEs than conventional farms; this was also confirmed by other authors (e.g.,[7,8,40]). The mean product-related emissions from organic farms are also lower but they vary broadly (see Table 7). It is quite possible that there are organic farms with higher product-related GGEs than their conventional counterparts. One reason among others is the broad variation of yields.

Conclusions

The results communicated in this paper refer to farms under organic and conventional management. The criteria for farm selection and the model-based analyses were not targeted at drawing general conclusions on the climatic relevance of organic and conventional farming or even at giving recommendations to policy-makers. The main emphasis was placed on testing the model software under practice conditions. The consideration of both organically and conventionally run farms was to allow the sampling of the largest possible range of management conditions. The results presented reflect only the system level crop production in the surveyed agricultural region.

Despite of this restriction, the investigations admit preliminary conclusions for the optimization of farm management and the reduction of GGEs. According to our results, organic farming includes a high potential of C sequestration, preferably by the growing of perennial legume–grass blends and the input of FYM. In conventional farming, legumes and FYM are nearly neglectable; humus balance sheets point to declining SOC values. In some farms, however, the situation may be completely different depending on crop rotation and technological design, and therefore, in the final run, recommendations and optimization strategies will always require a farm-specific approach. The farm as such has been in the focus of our studies, because management decisions taken at this level have effects on climate and environment. In order to mitigate emissions, problem areas must be identified with attention to farm specifics; subsequently, coordinated measures and strategies must be elaborated. In order to gain acceptance by the farmers, the possible economic and ecological consequences of the implementation of these activities must be predictable. The REPRO model is therefore oriented to an overall rating of farms according to multiple criteria. Besides the balancing of C, N and energy fluxes as described in this paper, further modules are under construction analyzing harmful soil compaction, erosion and biodiversity.

Under the umbrella of the German Agricultural Society, an organization for the promotion of technical and scientific progress in the food and agricultural sector with over 17,000 German and international members, more than 90 farms in the Federal Republic of Germany are currently testing the software, with the purpose of using it not only in research but in the future also in the management of farms.

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Financial relevance of organic farming payments for Western and Eastern European organic farms

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Abstract

Organic farming in the European Union has been supported widely since 1994. Against the background of discussions concerning the design and level of organic farming support, and the relevance of organic payments for the economic success of organic farms, the question emerges as to the impact of support payments on the sustainable development of organic farming in Europe. Different databases and methodological approaches have been chosen to demonstrate the role of organic farming payments for the viability of organic farms for selected Western and Eastern European study countries. Economic analyses are based on national Farm Accountancy Data Network (FADN) in the Western European countries and on 'typical farms' in the Eastern European group. As a supplement to the modeling analyses, a detailed survey of 50 organic farms was carried out in each of the study countries. Organic farming payments were assessed to be 'important' or 'very important' to the economic situation on farms by the majority of the farmers surveyed. The outcome of the economic analyses shows that organic farming payments contribute on average 4–6% of gross output in the Western European countries and 4–19% in the Eastern European countries studied. The results put the level of specific support for organic farming into perspective, as other support payments and market returns contribute larger shares of total farm revenue in all the countries analyzed. Organic farming payments account for 10–30% of family farm income plus wages in Western European study countries and—after EU accession—up to three-quarters in some of the Eastern European countries, thus highlighting the considerable vulnerability of organic farms to changes in organic farming policy. As a general trend in both the West and the East, it can be observed that the policy dependency of farms has increased over recent years. Changes in organic area support, which are actually under discussion in some countries, must be carried out with a sense of proportion, since support payments will continue to play an important role in the profitability of organic farms. Nevertheless, in order to reduce dependency on area payments, organic farming support should follow an integrated approach, using a mix of support measures including, e.g., the improvement of processing and marketing facilities, support for farm cooperation and activities designed to enhance demand.

Key words: farm economics, agricultural policy, financial support, organic farming, competitiveness

Introduction

Since 1994, organic farming has been promoted EU-wide through public funding. Subsequently, the entire sector has exhibited very dynamic development[1–4] and an increasing number of countries have implemented organic farming action plans[5,6]. These plans follow an integrated approach to varying degrees, including support in the areas of production, processing and marketing, consumer information and other measures. Nevertheless, despite these 'holistic' concepts, area payments for the introduction and maintenance of organic farming remain the predominant support measure in terms of government expenditure in almost all European countries. High policy dependency implies high risk when organic farming support decreases. Against the background of heightened discussion concerning the shape and level of organic payments, and their relevance for economic success, the question arises of their impact on the sustainable development of organic farming in Europe.

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Table 1. Organic farming area payments (for maintenance) in selected European countries (2003 and 2004/2005).

	AT	DE[1]	DK[2]	IT[3]	UK[4]	CH	CZ	EE	HU	PL	SI
2003					Euro/ha						
Arable land	327	102–255	81	111–600	0–51	527	63	45	79	57	345
Grassland/pasture	96–251	102–255	81	85–525	0–51	132	31	19/22	40	18	86/171
Permanent crops	799	358–924	81	298–900	0–44	790	110	128	83	114	517
Vegetables	509–654	128–410	81	295–600	0–51	790	63/110	128	79/83	92	443
2004/2005					Euro/ha						
Arable land	327	102–255	117	111–600	0–51	527	110	97	127	131	460
Grassland/pasture	96–251	102–255	117	85–525	0–51	132	34	74	59	57	230
Permanent crops	799	358–924	117	298–900	0–44	790	381	241	281	337	795
Vegetables	509–654	128–410	117	295–600	0–51	790	344	241	202	206	544

Source: Own compilation following[3–5].
AT, Austria; DE, Germany; DK, Denmark; IT, Italy; UK, United Kingdom; CH, Switzerland; CZ, Czech Republic; EE, Estonia; HU, Hungary; PL, Poland; SI, Slovenia.
[1] Payments in DE vary according to 'Bundesland'.
[2] DK has not offered specific organic farming maintenance payments since 2004. Instead, alternative agri-environmental support measures were introduced, in which mainly organic farms participate. The numbers presented here for 2004/2005 belong to this measure.
[3] Payments in IT vary according to region. In some cases there exist other (additional) classification, so that these numbers only can serve as an approximation.
[4] Payments in UK vary according to region (England, Scotland, Wales and Northern Ireland).

In this paper, first, the main features of organic payments are briefly presented. Following a description of the methodological approach adopted, the importance that farmers from different European countries attach to such payments is discussed, with regard to their decision to convert and the economic viability of their farms. On the basis of farm accounting data and farm models, the relevance of organic payments for economic success is subsequently analyzed. The results are then discussed within the framework of international competitiveness and the sustainability of organic farming development.

Organic Farming Payments in the European Union

Environmental goals constitute the primary aims of government support for organic farming. In addition, the contribution of organic agriculture to rural development, a reduction of production surpluses, consumer satisfaction and the exploitation of market opportunities are also regarded as highly significant and worthy of financial support[7–10].

Support for organically farmed area is one of various agri-environmental measures and is a part of the second pillar of the Common Agricultural Policy (CAP) of the EU. The relevance of these payments needs to be seen against the importance of total government support for agriculture in the EU countries. In terms of the EU agricultural budget, 90% went to the first pillar in 2003 and market support is generally the most important type of support to farmers[11]. For organic farming, however, price support accounts for a lower proportion of total transfers to producers than direct payments[12]. In most countries, area support is offered for conversion to organic farming and for the maintenance of this production system. As products cannot be sold as organic with price premiums in the first two to three years of conversion, payment rates for conversion are higher than those for maintenance in most countries[4]. According to the EU Regulation (EEC) 1257/1999[13] (Programme for Rural Development) payment rates per hectare are calculated on the basis of income foregone, additional costs resulting from the commitment given and the need to provide an incentive (maximum 20%). Due to the diverse natural, socio-economic and political conditions across Europe, both the design of measures and the level of payments vary widely between countries (see Table 1). In 2003, for example, maintenance payments for arable land varied from 44 Euro ha^{-1} in some parts of the UK, to more than 300 Euro ha^{-1} in Austria and Slovenia. The organic farming payments offered in Switzerland, the non-EU country, were even higher.

While changes between 2003 and 2004 were of minor relevance in Western European countries, the increase in payments in the new member states after EU accession is quite marked. In some countries, per hectare payments more than doubled. Thus, there is increased incentive for Eastern European farmers to convert to organic farming and statistics show that farmers did, and do, react to these incentives, set by policy-makers. All of the new member states have revealed notable growth rates in organic area over recent years[1].

Materials and Methods

The results presented here are based on a survey of organic farms, on information from national Farm Accountancy Data Networks (FADNs) and on the modeling of 'typical' organic farms in different European countries.

Table 2. Main characteristics of typical organic farms analyzed in selected Eastern European countries (2003).

	Total UAA (ha)	Share of grassland (ha)	Suckler cows (no.)	Milk production ($t\,yr^{-1}$)	Main products/ activities
Czech Republic					
Arable (large)	200	15	0	0	Cereals
Dairy (small)	64	16	0	58	Milk/beef
Cow-calf (small)	100	100	11	0	Cattle breeding
Cow-calf (medium)	140	100	70	0	Weaned calves
Cow-calf (large)	551	100	145	0	Weaned calves
Estonia					
Arable (large)	89	4	0	0	Cereals/sheep
Dairy (large)	230	74	0	194	Milk/beef/calves
Hungary					
Arable (small)	9	0	0	0	Vegetables
Arable (medium)	374	0	0	0	Vegetables/cereals
Dairy (medium)	290	16	0	335	Milk/cereals/processing
Dairy (large)	1850	22	80	3360	Milk/cereals
Poland					
Arable (small)	17	15	0	0	Vegetables/berries
Arable (large)	100	12	0	0	Cereals
Dairy (small)	17	24	0	34	Mixed
Dairy (medium)	18	28	0	88	Milk
Dairy (medium)	48	73	0	100	Milk/processing
Slovenia					
Arable (small)	13	23	2	0	Vegetables
Dairy (small)	13	100	0	28	Milk
Cow-calf (small)	9	100	6	0	Beef

Source: Own compilation.
UAA, utilizable agricultural area.

1. In the winter and spring of 2004, face-to-face interviews were conducted with 550 organic farmers from 11 European countries (Austria, Czech Republic, Denmark, Estonia, Germany, United Kingdom, Hungary, Italy, Poland, Slovenia and Switzerland). The farms were chosen at random on the basis of lists of all organic farms (Czech Republic, Denmark, Estonia and Poland) or datasets from certification bodies, ministries and farmers' associations, in most cases covering more than 90% of organic farms (Germany, Hungary, Slovenia and Switzerland). In Austria, Italy and the United Kingdom, a regional focus was created. All of the farms visited had started to convert to organic production before 2001 and had thus completed their conversion periods. For the most part, survey data were analyzed using descriptive statistical methods.
2. FADNs provide extensive information on economic indicators, including very detailed information about direct payments and revenues. As farm accounts provide data on the actual payments received, this data source implicitly allows analyses, for individual farms, of factors influencing eligibility for support and payment levels. With the exception of the UK, where data were available only for the year 2001, the availability of accountancy data for organic farms was good for the Western European countries analyzed. Generally, information was drawn from significantly more than 100 farms for five to eight consecutive years, thus allowing further stratification and the analysis of developments over time.
3. In the new member states, national databases like FADN data are still scarce for organic farms. This is why the typical farm approach was chosen in the analysis of organic farms for these countries[14–16]. According to this methodological approach, a small number of organic farms was selected, each of them representing a group of similarly structured farms. The typical organic farms reflect a large share of organic farming in their country. Following this concept, and depending on the structure of organic farming in the countries studied (Czech Republic, Estonia, Hungary, Poland and Slovenia), two to five typical organic farm models for the year 2003 were set up, based on the statistical data and expert knowledge (Table 2). Data collection took place on real farms and the scientists were always accompanied by local experts on organic farming, e.g., advisors, so that farm-specific data could be leveled out in such a way as to show the likely situation for a group of farms. Results for 2005 were generated through the inclusion of actual data concerning support payments, and general increases in costs for labor and other inputs into the models.

Several indicators exist for measuring economic success. In the EU, one of the measures of farm profits most widely used is family farm income (FFI) which provides information on the returns to land, labor and capital resources owned by the farm family. It is calculated as the difference between all farm returns and all incurred costs including depreciation. On family farms, most of the labor is supplied by the farmer and unpaid family members and thus has to be remunerated by profit. On farms organized as limited companies or cooperatives, which are of particular relevance in some of the new member states, employed labor dominates and related wage expenses are part of costs. It would be misleading to compare FFI between farms of different legal structures so, consequently, FFI plus wages (FFI+W) was chosen for the following comparisons.

In order to evaluate the relevance of organic farming payments to the economic success of organic farms, two main indicators were used:

- the relationship between payments and gross output, providing an impression of the contribution of payments compared with other revenues, e.g., from sales. This measure can be seen as an indication of the level of 'organic farming policy' dependency as compared with 'market' and 'other policy' dependency;
- the ratio of payments relative to FFI, or to FFI+W, which quantifies the dependency of profits on organic payments. This measure can be seen as an indicator of farm vulnerability to changes in specific support policies.

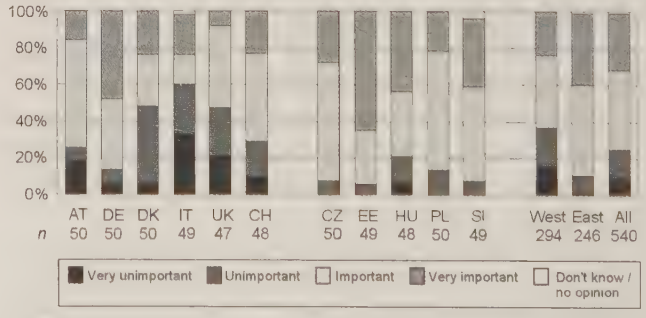
However, when evaluating the importance of organic support payments, it must be noted that abolition of maintenance payments for organic farming does not automatically imply that the income of organic farms will be correspondingly reduced. In many European countries, organic farms are likely to be eligible—and apply—for other agri-environmental payments, e.g., for the extensive use of grasslands or the elimination of fertilizers and/or pesticides on arable land, without having to change their farm organization. The extent of the resulting payments is difficult to assess, as programme availability, eligibility criteria and payment levels show a very high regional variation[3,4]. In this study, as an approximation, it is assumed that organic farms would be eligible to receive at least the same amount of agri-environmental payments as comparable conventional farms, if no specific support for organic farming existed. Thus, the benefit of specific support to farms for organic farming, dubbed 'extra payments for organic farming' in the following analysis, is given by the difference between agri-environmental payments to organic and comparable conventional farms (see [17] for the notion of 'comparable conventional farms'). This approach actually provides an upper estimate of the importance of extra payments for organic farming, as it seems likely that organic farms may often be eligible for more agri-environmental funds than comparable conventional farms, without needing to change their production system. Due to limited data availability in Eastern Europe and the less widespread occurrence of agri-environmental measures which are non-combinable with organic farming support, this concept for the assessment of extra organic payments was restricted to the analysis of Western European countries.

While the methodology employed in the farm survey was exactly the same in every country and all farmers received the same questionnaire, the analysis of farm financial data in Eastern and Western countries used different databases and methodological approaches although employing the same economic indicators.

Farmers' Perception of Organic Farming Payments

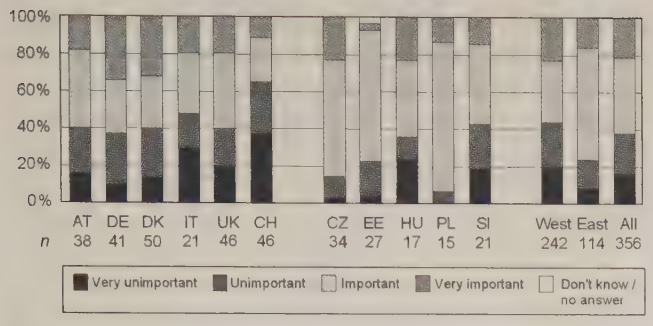
Farmers were asked to assess the importance of organic farming payments to the economic viability of their farms. The majority of farmers indicated that organic support payments were 'important', with 30% saying they were 'very important' (Fig. 1). Organic farming payments were considered to be important for farm viability more frequently in new member states than in the West. However, there were significant variations within the group of Western European countries, with German farmers attaching the greatest importance to payments overall. In line with the relatively low payment levels in the UK and Denmark, approximately half of the farmers in these countries indicated that such support was not important to economic viability. Somewhat surprisingly though, 60% of the farmers surveyed in Italy went along with this assessment, the reason being that, Italian farmers cultivate a high share of permanent crops [37% of utilizable agricultural area (UAA) on average of the farms] with a high gross output, such as olives, wine and citrus fruits, thus rendering payments less significant.

Among Eastern European countries variations were much smaller, with less than 10% of farmers assessing organic farming payments as 'unimportant' or 'very unimportant'.



n: number of farmers answering.
(1) Question asked: What is the significance of the organic farming payments for the economic viability of your farm today?

Figure 1. Farmers' perception of the significance of organic farming payments for the economic viability of their farm today(1). Source: own calculations based on farm survey winter/spring 2004.

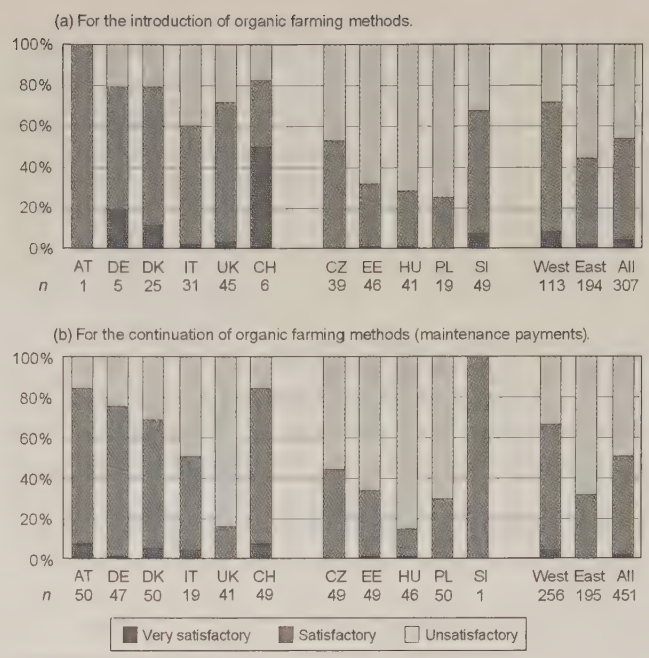


n: number of farmers answering.
(1) Question asked: how important was the availability of organic payments in your decision to convert?

Figure 2. Farmers' assessment of the importance of the availability of organic payments in their decision to convert[(1)]. Source: own calculations based on farm survey winter/spring 2004.

Asked about the importance of the availability of organic farming payments in their decision to convert, farmers from the West and the East who received such payments when they converted gave different responses. At least 56% of the Western European farmers felt that organic farming payments had been important or very important, compared with 76% of their Eastern European counterparts (Fig. 2). In the West, the proportion of farmers describing organic farming payments as being either unimportant or very unimportant in their move towards conversion was highest in Switzerland (65%) and lowest in Germany (37%). Among Eastern European farmers, organic payments were felt to be most important by Polish farmers (93%) in the decision to convert. In Poland organic farming payments were the only area payment available to farmers before accession.

Assessment of current levels of support to organic farming was mixed, with approximately half of farmers saying that it was 'satisfactory' or even 'very satisfactory', and the other half registering dissatisfaction (Fig. 3). Particularly with regard to this question, strategic responses could be expected on the grounds that assessing payment levels as being too low might help foster an increase in, or at least a continuation of, current payment levels. Thus, the high overall level of satisfaction with actual payments (56%) is remarkable. With the exception of the UK, where maintenance payments are much lower than those for conversion, there were no large differences between evaluation of payment levels for the introduction and maintenance of organic farming. There are, however, considerable differences between countries. In general, farmers in Western Europe appear to be more satisfied than those in the new member states, where low approval ratings with respect to payment levels prevail, especially in Estonia, Poland and Hungary. However, these results were obtained from a survey conducted in early 2004, before EU accession of the Eastern European countries and before the increase of organic farming payments.


(a) For the introduction of organic farming methods.
100%
80%
60%
40%
20%
0%
AT DE DK IT UK CH CZ EE HU PL SI West East All
n 1 5 25 31 45 6 39 46 41 19 49 113 194 307
(b) For the continuation of organic farming methods (maintenance payments).
100%
80%
60%
40%
20%
0%
AT DE DK IT UK CH CZ EE HU PL SI West East All
n 50 47 50 19 41 49 49 49 46 50 1 256 195 451
Very satisfactory
Satisfactory
Unsatisfactory

n: number of farmers answering.
(1) Question asked: how would you judge the current level of organic payments for the introduction/continuation of organic farming methods for your farm?

Figure 3. Farmers' assessment of the current level of organic payments[(1)]. Source: own calculations based on farm survey winter/spring 2004.

Farms' Dependency on Organic Farming Payments

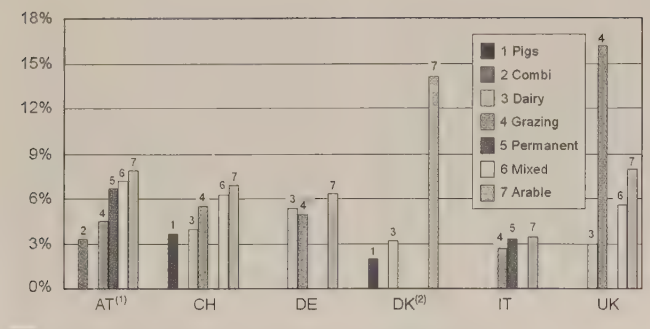
This section will analyze the relevance of organic farming payments according to different farm types and time periods. For organic farms in Western European countries, time series data from national FADNs were analyzed, enabling the impacts of different policy decisions and economic circumstances to be described. In the Eastern European study countries, analyses are based on typical farm modeling and concentrate on a comparison of the situation before and after EU accession.

Generally, the indicators for policy dependency show great variation between farms. This depends not only on the payments received, but also on the respective levels of gross output and profits which, in turn, vary with farm type and size (Table 3, Figs. 4 and 5, and Table 4).

Table 3. Share of extra payments for organic farming in gross output, FFI and FFI + W in selected Western European countries, 2001.

	% in gross output	% in FFI	% in FFI + W
Austria	5	13	12
Denmark	4	72	32
Germany	6	28	19
Italy	5	16	n.a.
Switzerland	4	11	10
UK	6	47	28

Source: own calculations based on national FADNs.

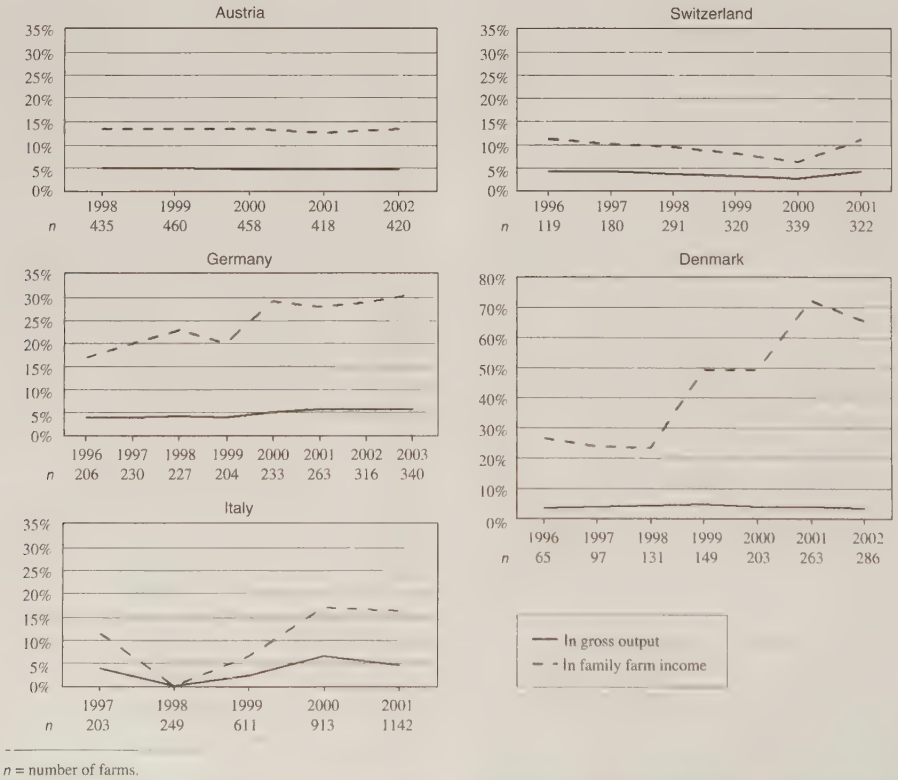


(1) Combi = farms with more than 25% of total standardized gross margin from forestry.
(2) Values for farm type 'Pigs' extrapolated from 2000 + 2002.

Figure 4. Share of extra payments for organic farming in gross output by farm type in the selected Western European countries, 2001. Source: own calculations based on national FADNs.

Consequently, a generalized comparison can only be made between Western European countries, where the large farm samples from FADNs allow aggregation. Table 3 provides an overview of the importance of the extra payments for organic farming in these countries, measured as the contribution to gross output. In some countries, even though the absolute level of specific support to organic farms is high[4], the relative preference for organic agriculture is low and remarkably similar across countries, ranging from 4% in Denmark to 6% in the UK. This is because of the existence of other agri-environmental programmes with high payment levels, for which organic farms would be eligible if the specific organic support measures did not exist. However, if measured as a percentage of FFI, the importance of specific support to organic farming is high in Germany, and very high in the UK and Denmark, highlighting the vulnerability of the organic farms in these samples to changes in specific support policies.

The ranking of farm types according to the share of extra support payments for organic farming in gross output is remarkably similar in all Western countries (Fig. 4). The only exception is the very high value for organic grazing livestock farms in the UK, which is a result of the comparatively low level of gross output on these farms while, at the same time, the level of agri-environmental payments is relatively high due to the combination of those from the Organic Farming Scheme and other agri-environmental schemes. The contribution of such support to gross output is highest for arable farms, due partly to the fact that the participation of conventional arable farms in agri-environmental programmes is still the exception. In combination with the approach chosen in this study to approximate the extra value of organic support programmes, this leads to high values. Where non-organic agri-environmental programmes support the extensification of arable farming, the relevance of specific support to organic arable farming in the respective regions will be correspondingly reduced. The importance of extra support payments for organic farming is lowest for the pig farms,



n = number of farms.

Figure 5. Development of the share of extra payments for organic farming in gross output and FFI in the selected Western European countries, all farms. Source: own calculations based on national FADNs.

highlighting the high degree of market-orientation of organic pig production.

For Western European countries, analysis of the historical development of the importance of specific support payments for organic farming was possible, based on national FADN data for several years. According to the results given in Figure 5, the share of extra payments for organic farming in gross output and FFI in Austria is comparatively stable for the years 1998–2002, reflecting the continuity of support policies and sample composition. The share of specific support in gross output even decreases slightly. In Switzerland, the importance of specific support payments declines until 2000, reflecting the continuously improving market situation for organic products since the beginning of the 1990s, and an increasing share of market revenues in total output. In 2001, the share of extra support payments increased, as the level of support payments for organic farming was raised. In Germany, the importance of support has been growing significantly over the years, reflecting increased payment rates for organic farming within the agri-environmental programmes. In Denmark, the share of payments in gross output remains stable, while the contribution to FFI rises quite dramatically over the period. This development is due to the decline in average FFI over the years. In Italy, the time series data reveal a drop to zero in the share of extra payments for organic farming in 1998. This can be attributed to the difficulties experienced by many farms with respect to the transition from the first five-year contracts, according to the EU Regulation (EEC) 2078/92, to new contracts. The importance of specific organic farming support in farm performance has been increasing since then.

The focus of analysis for the Eastern European countries is the significance of payments before and after accession to the EU. Organic farming payments accounted for 4–19% of gross output in the selected new member states before accession (Table 4). There are large differences between countries, however, the share being notably lowest in Poland, corresponding to low organic area payments for arable and grassland. On almost all typical farms, the share of organic farming payments in gross output increased after accession.

There are some typical farms, particularly in the Czech Republic where the importance of organic farming payments to total farm returns decreases over the time period under consideration. The reason is a marked increase in direct payments other than those for organic farming, in the course of the adoption of the CAP. The declining relevance of organic payments is thus a relative, rather than an absolute, phenomenon. By 2005, the significance of organic payments in the gross output of Polish farms is about as high as that of other countries. Looking at the

Table 4. Share of organic farming payments in gross output and in FFI + W in selected Eastern European countries, 2003 and 2005.

	% in gross output		% in FFI + W	
	2003	2005	2003	2005
Czech Republic				
Arable (large, 200 ha)	17	18	63	44
Dairy (small, 58 t milk)	12	14	76	34
Cow-calf (small, 100 ha)	11	6	37	11
Cow-calf (medium, 140 ha)	8	6	11	8
Cow-calf (large, 551 ha, 145 cows)	12	8	32	13
Estonia				
Arable (large, 89 ha)	9	23	36	69
Dairy (large, 194 t milk)	11	20	61	86
Hungary				
Arable (small, 9 ha)	4	8	9	18
Arable (medium, 374 ha)	9	12	21	23
Dairy (medium, 335 t milk)	6	5	14	10
Dairy (large, 3360 t milk)	5	7	15	16
Poland				
Arable (small, 17 ha)	4	9	6	13
Arable (large, 100 ha)	9	16	17	29
Dairy (small, 34 t milk)	9	14	20	32
Dairy (medium, 88 t milk)	5	10	11	21
Dairy (medium, 100 t milk)	4	8	9	14
Slovenia				
Arable (small, 13 ha)	14	18	27	35
Dairy (small, 28 t milk)	19	21	72	74
Cow-calf (small, 9 ha, 9 cows)	12	14	132	80

Source: own calculations based on typical farm modeling.

share of such payments in farm profit (FFI+W), it is clear that many typical organic farms were already highly vulnerable to changes in organic farming policy before accession. This holds true particularly for organic farms in the Czech Republic, Estonia and Slovenia. Following EU accession and higher payment rates, there is increasing vulnerability to policy changes on farms in Estonia, Hungary and Poland. In the Czech Republic and Slovenia, changes in vulnerability to organic farming policy depend on farm type.

In discussing these results, changes in overall agricultural policy caused by the adoption of the CAP must be stressed (for background information see[18–20]); other than organic farming, direct payments increased more than organic payments in all of the typical farms after EU accession, and thus their relevance for the economic success of typical organic farms[17].

Discussion and Conclusions

The results show that organic farming payments are important in all European study countries and that policy dependency has increased over recent years. Generally, the degree of policy dependency in the Eastern countries (Table 4) is equal to or higher than that observed in the Western countries (Table 3) even before accession to the EU and this is reflected in farmers' assessment of the significance of organic farming payments for the economic viability of their farms (Fig. 1).

However, these findings put the level of specific support for organic farming into perspective, as other support payments and market returns contribute larger shares to total farm revenue in all the countries analyzed. In this respect, a further important outcome is confirmation that high organic payment levels do not, automatically, imply a strong preference for this farming system. Particularly in the Western European countries, there are often attractive, competitive and non-organic schemes within agri-environmental programmes which reduce the incentive for conversion. Looking at the future, organic farming payments will continue to play an important role in the profitability of organic farms in Western Europe after implementation of the 2003 CAP reforms. In the East, the importance of organic farming payments is likely to remain at a high level, as long as organic farming payment rates remain unchanged.

The different development of payments and costs in the countries analyzed is likely to affect the international competitiveness of organic farms. Future organic market shares could therefore be distributed quite differently, in comparison with today. There still remain marked differences in absolute levels of support—referring not only to organic farming payments—for organic farms in different countries, which may significantly influence the competitiveness of organic farms on the international markets. Higher payments may foster investment in production technology, thus improving productivity and also, perhaps, quality; therefore, those organic farms benefiting from more generous support will be able to gain market shares at the international level. Additionally, farmers receiving relatively high payments might possibly be able to offer their products at lower prices.

Nevertheless, it must be stressed that organic farming payments are granted to organic farmers because they offer environmental services to society. These services amount to positive external effects (e.g., protection of water, biodiversity)[21–25] compared with mainstream agriculture. Different payment rates between countries may reflect different social priorities, and could be argued to be the consequence of variations in the value placed on environmental goods by different countries. An argument therefore exists for treating the varying organic farming payments as a consequence of different socio-economic conditions, and for accepting them in the same way as, for example, different wage levels.

Future support for organic farms is likely to be different from today, although the direction of change is far from certain. On the one hand, continuing CAP reform, intended to strengthen sustainability and the second pillar of the CAP, will offer a wider range of opportunities to support organic farming. On the other hand, whether these opportunities will be matched by corresponding funds or not is an open question; despite modulation, cash-strapped public finances may prevent a more widespread support of organic farming via the second pillar.

Improvement of the economic situation on organic farms in the new member states will give farmers the opportunity to invest in production technology and to catch up with their Western colleagues with respect to quality standards. However, in the face of ongoing discussions concerning support payments, farmers run a high risk when undertaking far-reaching investments. Rather than merely relying on area support, policy should supplement organic farming area payments with a mix of additional support, including measures for the improvement of processing and marketing facilities, the support of farm cooperation and for enhancing demand.

Acknowledgements. The work underlying this paper has been carried out with financial support from the Commission of the European Community under Key Action 5 of the Fifth Framework Research and Technological Development Programme for the project 'Further Development of Organic Farming Policy in Europe, with Particular Emphasis on EU Enlargement'. We are grateful for this support. This paper does not necessarily reflect the views of the European Commission, and in no way anticipates the Commission's future policy in this area. Its content is the sole responsibility of the authors. We are grateful to two anonymous referees for their helpful comments.

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Value in the values: pasture-raised livestock products offer opportunities for reconnecting producers and consumers

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Abstract

Pasture-based livestock production holds promise in helping to reinvigorate small and mid-scale farming, as well as farm communities, across the United States. In this study, in-depth interviews of pasture-based livestock producers, meat processors and buyers were conducted to determine behaviors, attitudes and expectations with regard to pasture-based livestock production. In addition, consumers were polled to determine their attitudes with respect to how food animals are raised and treated. Results revealed many shared values between those involved in raising, processing and distributing animal products, as well as consumers, indicating an opportunity for a 're-embedding' of livestock production based on these shared values. The concurrent development of both direct and extended markets, e.g. values-based value chains, is suggested as one way of addressing the difficulties faced by individual farmers in processing and distributing animal products with their provenance and underlying values intact.

Key words: pasture-based livestock production, farmers, consumers, family farm, animal welfare, values-based value chains, short food supply chains, direct markets, re-embedding

Introduction

A number of studies have shown a link between the social and economic well-being of rural communities and the presence of entrepreneurial, independent small and medium-sized farms[1,2]. However, agricultural censuses show a decline in the number of farms across the United States, particularly those between 50 and 1000 acres[3]. One strategy of agriculture that holds much promise in reinvigorating these small and mid-scale farms is pasture-based livestock production. This model, requiring lower initial investment and debt, offers opportunity for beginning or diversifying farms and the ability to earn a living on a relatively small scale[4,5].

Pasture-based production is associated with many social benefits in addition to offering a more humane alternative to the confinement model[6,7]. This system has many potential environmental benefits as well; studies have shown that, compared to row crop production within similar landscapes, pastures can reduce sediment erosion[8], phosphorus runoff[9] and improve carbon sequestration[10]. Thus, for this study, we conducted an intensive investigation of pasture-based animal production, distribution and consumption in Michigan to better understand some of the opportunities for and barriers to the expansion of direct and extended markets for these products, as well as to develop viable strategies for maintaining small and mid-sized farm viability.

Previous Research

This study follows from recent scholarship that has documented the desire to create alternatives to the present industrial-commodity model of agricultural production and distribution. Researchers have identified demands for alternatives to industrialized production as typically stemming from some combination of concerns over food safety and human health, animal welfare and the environment[11–15]. Murdoch et al.[16] discuss this as a reaction against the tendency for industrial agriculture to outflank nature, through the appropriation of practices and substitution of ingredients in place of natural ones. Recognition of these issues in industrialized agriculture and its products has resulted in calls for food to be 're-embedded' in nature.

In reaction to the global commodity distribution system, scholars have also called for a 're-embedding' of food in

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community or society. This often takes the form of demand for locally produced products[14,17]. The relationships between farmers and consumers, based largely on a shared set of ethical and moral values (e.g. commitment to locality, ecological sustainability and animal stewardship considerations), are critical in adding transparency, trust and, ultimately, meaning to the food system[14,18,19]. It is theorized that transactions based on shared values between farmers and consumers will result in food that is re-embedded in both nature and community: what Sage[18] calls 'good food': 'authentic, derivative of a place or person(s), produced with regard to naturalness and animal welfare, which is not only nutritionally sound, which is good to eat but also ... food that is "good to think"' (p. 51).

An obvious question is how can 'good foods' reach consumers with their provenance and underlying values intact? Direct markets provide an obvious solution; face-to-face transactions where communication, trust and relationship building can more readily take place[13,20]. However, only a limited number of consumers are likely to go out of their way to seek and buy products from direct markets[21]. As a result, more complex mechanisms are needed to facilitate the transmission of transparency, trust and meaning along with the food products, which may involve more informative labeling efforts and/or the construction of 'values-based value chains'[22–24].

In this study, we investigated pasture-based livestock production with three main questions in mind: (i) What are the opportunities and obstacles for this form of livestock production from the perspective of farmers, processors and distributors? (ii) What, if any, are the shared values that exist between producers and consumers with respect to pasture-based animal products? and (iii) What opportunities and obstacles exist for the further development of direct and extended markets for pasture-based animal products? To these ends, we conducted in-depth interviews of pasture-based livestock producers, meat processors and buyers to determine their practices, attitudes, beliefs and expectations of livestock production and processing in general, and pasture-based production more specifically. In addition, consumers were polled to determine their attitudes with respect to how animals are raised and treated for their consumption, as well as their receptivity towards products derived from pasture-raised animals. Given the broad international interest in re-embedding food systems in society and nature, as well as in developing networks of 'quality' foods, we believe our findings will be broadly relevant to those seeking to identify new strategies for achieving these goals.

Methods

This study used two distinct methodologies to query two main stakeholder groups associated with pasture-raised animal production: those in the supply chain that produce, process and deliver the products, and the end consumers of those products. We utilized qualitative, open-ended interviews of supply chain actors to gather a first hand, in-depth account of their experiences; revealing the attitudes, beliefs, goals and motivations of those operating in this market. In addition, key issues raised during these interviews were used to inform a quantitative telephone survey of a representative sample of Michigan residents with respect to animal products in general, and pasture-raised animal products more specifically.

Table 1. Type of animals raised on farms in the study ($n = 16$).

Animals raised	Number of farms	Percentage (%) of farms
Dairy cattle	4	25
Beef cattle	4	25
Lambs	1	6
Poultry	1	6
Mix	6	38

The farmers were selected for interview from a number of sources: (i) those identified by the Chair of Michigan State University Extension's Forage/Pasture/Grazing Area of Expertise Team, (ii) members of the Michigan Hay and Grazing Council, (iii) farms listed on eatwild.com and (iv) peers of those farmers who had been previously interviewed. Interviewees were chosen to ensure a broad diversity of backgrounds, e.g. size of farm, number of years in operation, geographic location in Michigan, animal species raised, as well as age and gender of farmers. A total of 24 farm families were initially identified, and of these the authors were able to arrange interviews with 16 farmers and farm families, all of whom sell some form of differentiated pasture-raised animal products to local markets. Two of the 16 farms in this study use pasture sparingly, but support and primarily utilize a confinement model. Most farms produce a number of livestock products (Table 1) and utilize managed pastures containing grasses, legumes and other herbaceous plants.

Processors were sampled from those identified by the farmers in this study, plus several others known to the researchers, for a total of eight individuals interviewed (with one refusal from those initially identified). Finally, buyers and distributors were selected from those known to sell pasture-raised products, including two distributors, two chefs and two retailers, for a total of six individuals (with one refusal from those identified initially). While these samples are not statistically representative of any larger group, such 'purposeful sampling'[25] brings both the diversity and depth of data needed to understand the questions at hand.

All interviews were conducted by the primary author, and, with two exceptions (one farm family and one processor), the interviews were taped and transcribed. The interviews were conducted from the fall of 2004 to the spring of 2005.

Introductory issues covered during the interviews were initially identified through literature review. All

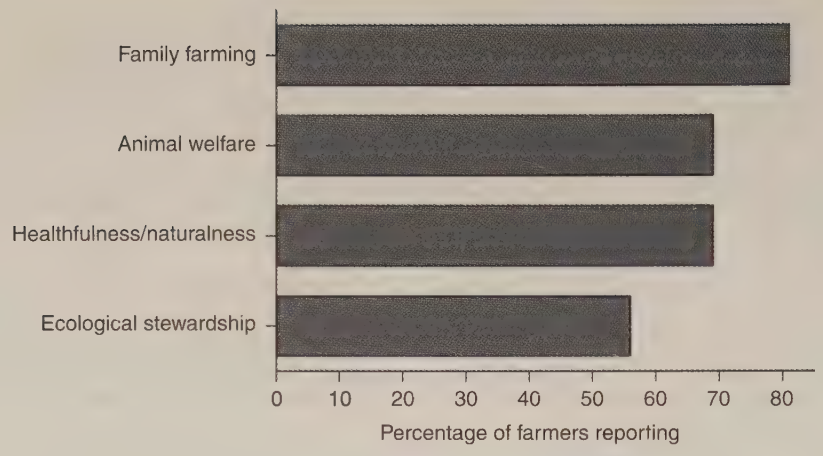

Figure 1. Values associated with pasture-based animal production as reported by Michigan farmers ($n = 16$).

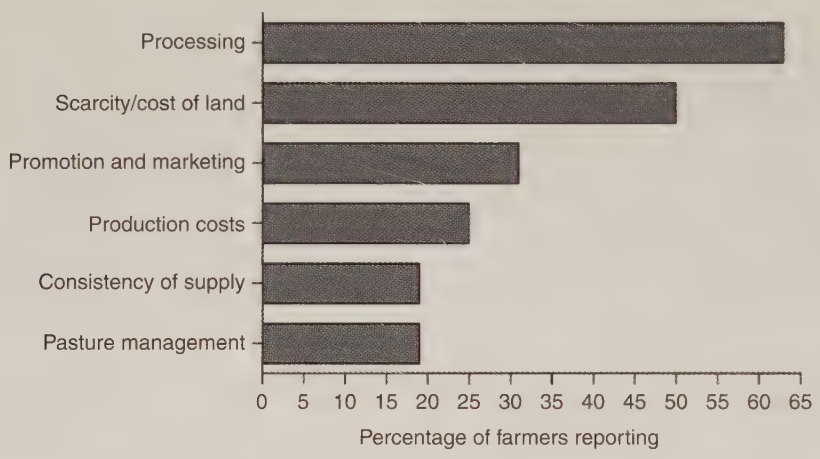
Processing
Scarcity/cost of land
Promotion and marketing
Production costs
Consistency of supply
Pasture management
0 5 10 15 20 25 30 35 40 45 50 55 60 65
Percentage of farmers reporting

Figure 2. Challenges faced by Michigan farmers in meeting consumer demand for products from pasture-raised animals ($n = 16$).

interviewees were asked to identify the strengths, weaknesses, opportunities and threats concerning their businesses, as well as perceived research needs. Specifically, farmers were questioned about production, processing and marketing practices; processors were asked about business history and operations, including the role of inspection regulations. Finally, buyers were asked about their procurement practices, including experiences of working with small or local farmers, and their perception of consumer preferences. Copies of the qualitative interview guides are available from the authors.

Results from the qualitative interviews helped to inform questions for a statewide survey of Michigan residents, the goal of which was to measure consumers' preferences for various attributes of animal products in general, as well as their awareness and behavior concerning pasture-raised products more specifically. The survey included ten questions on consumer preferences, as well as general socio-demographic variables, including age, gender, income, education, marital and employment status, community type (e.g. urban versus rural), race and political affiliation. For six of the survey questions, respondents were asked to rate the importance of a series of food attributes using a 5-point Likert scale. The remaining questions covered consumers' purchasing habits and perceived health benefits of pasture-raised animal products. Copies of these questions are available from the authors.

The survey data were collected as part of the quarterly 'State of the State' Telephone Survey administered by the Institute for Public Policy and Social Research (IPPSR) at Michigan State University (MSU) in Fall 2005. A total of 988 Michigan residents were interviewed and the refusal rate was 21.5%, with a margin of error of ±3.1% (at the 95% confidence level)[26].

Results

Pasture-based livestock producers

Two main themes emerged from the in-depth interviews with farmers: (i) values of importance to farmers in the production of pasture-based animal products (Fig. 1); and (ii) challenges faced in getting these products to consumers (Fig. 2).

The 'Family farming' category in Figure 1 refers to an array of similar values that are associated with being able to

farm as a family, e.g. quality of life, producing products that can be afforded by all and contributing to the well-being of a community. Many have enjoyed relatively long tenures raising livestock on their farms, with little or no off-farm income. For those interviewed, 'quality of life' was often derived through doing enjoyable work, and being able to spend time with family. Several of the young farmers home school their children and see the farm as an essential part of their education: 'there's education going on all the time here'. One respondent expressed the value of 'not trying to get rich; we're trying to produce a product that almost everyone can afford', a sentiment echoed by other farmers as well.

Pasture-based farmers also perceive themselves as being embraced by their neighbors, and are happy to be an important part of the rural landscape. 'Not only do neighbors have no grounds for complaint, many are delighted by the sight of grazing animals'. The interviews also revealed that many farmers were concerned about the welfare of their animals and had taken steps to ensure they were as free from stress as possible; this is often expressed in religious or spiritual terms.

The farmers prided themselves on the 'healthy' and 'natural' quality of their products, emphasizing the lack of hormones or antibiotics; many of their consumers come to them with pre-existing health concerns, sometimes referred to them by doctors. Raising what they perceive as high quality, healthy and safe products is a key motivation as many farmers emphasized that they feed their families and friends, 'I know I'm clean, I feed them to my kids'; 'We don't sell anything in the store that we don't eat'.

Ecological stewardship was another commonly expressed value. One interviewee strongly believed in 'working with nature instead of conquering her'. Another felt it was important to 'give back to the land what is taken from it'; meaning that 'you're sensitive to the inputs and outputs and you're treating the environment and animals with respect ... everything works together, you're a steward of the land'.

Despite the benefits these farmers bring to their consumers and communities, they reported numerous challenges faced in bringing products to market, most notably access to appropriate processing facilities (Fig. 2). Farmers often had to drive long distances and schedule processing months in advance; encountering conflict with processors who only want to deal with large volumes of animals, or finding themselves in competition with deer hunters at a time when custom butchering services are most needed.

Finally, many farmers indicated a lack of materials and guidelines for communicating with consumers in the marketing and promotion of their products. Several expressed a need for help with raising public awareness of the importance of supporting local farmers, especially those using sustainable methods like pasture-based management.

Processors

The farmers generally have good relationships with the processors they use. They see the butchers as partners, having an important role in satisfying customers. The processors interviewed for this project are of the scale typically used by farmers who wish to merchandize their own meats (rather than selling them to commodity channels); they process meat from grain-fed as well as pastured animals. These processors either have continued a multi-generational family business, or in some cases, entered this business because they are committed to animal agriculture and saw a need for their services. They generally see farmers as partners and share their commitment to humane and stress-free handling.

Processors work with farmers to ensure high quality products, especially when the meat will be sold at the processor's own business. 'We know the farmers we do business with. We can tell you what their barns look like on the inside. We do need to know what type of animal they have, how they're fed. We just don't go out and say yes we'll buy it. We need to know its breeding, care, the farm area where it has been living, age, we're very picky.'

The current seasonality of production makes it difficult to retain labor. Many processors discuss being at full capacity only in the late summer and fall. 'By the time you've got somebody trained, you've moved out of the busy season and you're into the slow time and you can't afford them. So you're understaffed all the time.' Another says, 'Every slaughterhouse is backed up at the same time'. This also constrains the ability of processors to buy from local farmers to supply wholesale accounts.

Processors had mixed feelings about pasture-raised animals. A common dilemma is that the meat can be tough, and the lack of fat on the carcass precludes longer aging times. 'Grass-fed is a very nice animal. It does not have the marbling through it that a grain fed animal would have. It will not last aging as long as a grain fed. And most times it's not as tender.' Some processors commented that the animals' breed and farmers' practices do help to improve the quality of pasture-raised products.

Buyers and distributors

The buyers generally liked the idea of sourcing from local farmers, but have experienced many problems when trying to do so. These problems include: (i) small farmers and chefs/retailers lacking the time to seek each other out, (ii) finding markets for the whole animal, rather than just steaks and cuts, (iii) fresh, pasture-raised products are available only at certain times of the year and (iv) many consumers consider pasture-raised meat to be gamey and tough.

Consumers

Over 90% of respondents in the phone survey ranked animal products raised in an environmentally friendly and humane manner as very or somewhat important; and 87%

Table 2. Ranking of animal product attributes by Michigan consumers ($n = 988$) using a 5-point Likert scale (1 = very important, 2 = somewhat important, 3 = neutral, 4 = not very important and 5 = not important at all). Note that percentage values may not add to 100 due to rounding.

Attribute	Very important	Somewhat important	Neutral	Not very important	Not important at all
Environmentally friendly	65%	28%	2%	4%	1%
Humane treatment	63%	29%	2%	4%	3%
Raised without hormones or antibiotics	63%	24%	3%	7%	3%
Raised on a family farm	30%	33%	4%	25%	9%
Raised in Michigan	23%	29%	3%	27%	18%
Knowing the farmer who raised it	17%	17%	2%	32%	32%

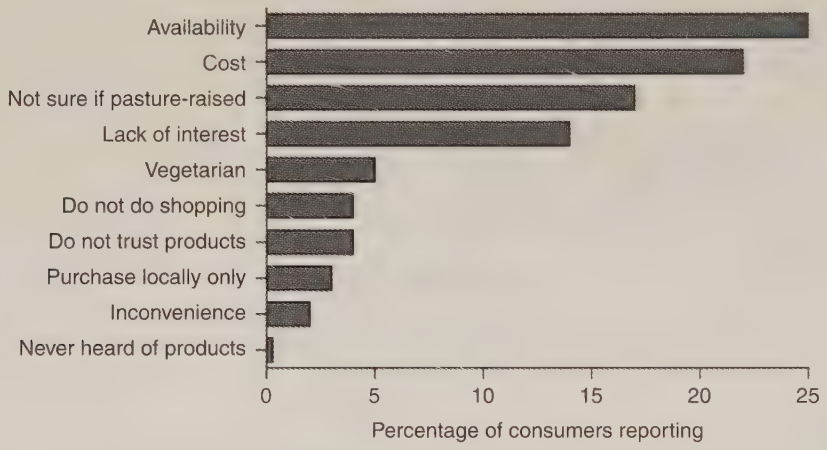

Figure 3. Most common reason cited by Michigan consumers for not purchasing or not purchasing more pasture-based animal products ($n = 494$, with 145 don't know/refused). Note that those consumers who always buy pasture-raised products were not asked in this question.

responded similarly to the 'hormone free' attribute (Table 2). Less than 10% responded that these attributes were not important. Knowing where these products come from was also ranked highly; 63% of respondents thought that it was somewhat or very important that animal products come from a family farm, and just over 50% indicated a desire for these products to be Michigan-raised. In contrast, approximately 64% of respondents said that it was not important to know the farmer who raised the animals.

Survey results also indicate that consumers believe they are already buying pasture-raised products; when asked how frequently they buy pasture-raised products, 39% said always or most times, while 35% said sometimes; only 26% said rarely or never. Respondents were also asked to indicate the top reason why they never buy, or do not buy more, pasture-raised products (Fig. 3). The most common reasons given were: lack of availability (25.3%), price (21.5%), not aware or not certain if item is pasture-raised (17.3%) and lack of interest (13.5%).

Consumers also associated pasture-raised animal products with healthfulness; with 76% strongly or somewhat agreeing that pasture-raised products are healthier for consumers than those from confinement operations (Fig. 4).

Discussion

Reconnecting consumers and producers

Pasture-raised products provide a significant opportunity to reconnect producers and consumers through shared values and a growing commitment to an environmentally, ethically and socially just food system. This is particularly important because of the increasing interest among consumers to reconnect with agriculture and to seek foods that are produced outside of traditional commodity channels and that encompass values that are beyond traditional market considerations. In addition, many farmers are seeking ways to avoid the often adversarial, unreliable and unrewarding relationships that are associated with commodity production. In this study, the values identified as most important by pasture-based farmers were echoed in the top-ranked product attributes identified by consumers: humane treatment of the animals, environmentally friendly production methods, 'naturalness' (no hormones or antibiotics) and produced on a family farm. Great opportunity lies in the fact that pasture-based agriculture can bundle these four desirable attributes into a single product. However, given that many survey respondents stated, almost certainly erroneously, that they are already buying pasture-raised products, there appears to be great need for information that

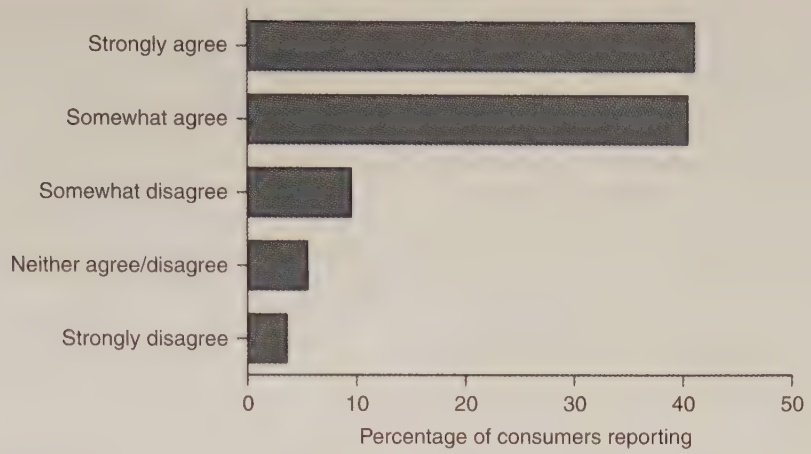

Figure 4. Consumer agreement with the statement 'Pasture-raised products are healthier for consumers than products from confined feeding operations' ($n = 919$, with 69 don't know/refused).

helps consumers become aware of the important values associated with pasture-based production as well as to identify them in the marketplace.

These obstacles and concerns can be addressed with a broad consumer education and marketing campaign that highlights the shared values as well as the important social, environmental and health benefits of pasture-based livestock production. However, given the comments of processors and distributors in this study, these efforts should also include issues of seasonal variability in the availability and characteristics of pasture-based animal products in general, as well as appropriate preparation and cooking techniques for pasture-raised meats more specifically.

A recent study indicates that consumers overwhelmingly prefer to obtain this information at the point of purchase, and that the preferred sources of this information are labels, brochures or retail displays[27]. For pasture-based animal products, these efforts could stand apart from more 'conventional' labeling or marketing efforts through a focus on 'process over product' as well as encompassing a wider variety of values than those typically found within the marketplace[22]. However, it is important that this new role for labeling and marketing be supported by a shared commitment to transparency and openness from all elements of the supply chain, or consumer trust in the process will eventually be eroded away[28]. Value chains show promise in delivering pasture-based products to consumers while retaining the trust and transparency once associated with more intimate farmer–consumer relationships.

Delivering pasture-based products to consumers

As demand for 'good food' increases, distribution channels will need to keep pace; both direct and extended markets need to be developed. Farmers' markets and the like can serve as an entry point to a 'new food economy' for consumers; a place to experience the food stories, sample products, get recipes and cooking/handling tips, meet the farmers and form relationships. However, given the habits of modern consumers, the growth of direct markets in meeting this demand will almost certainly have limits; only a small proportion of people will likely go out of their way to shop for and prepare food from these sources[21]. Addressing what Renting et al. refer to as the 'contradictory hybrid consumer demands of convenience and quality'[13] will require new distribution chains to bring pasture-raised products into more mainstream retail sites like supermarkets, as well as mechanisms, (e.g. labels, as described above) to communicate the 'story of the food' and to establish the meaning for and relationships with consumers, thus inhibiting the commoditization of the products[22].

The concept of value chains[23,24] is particularly promising in that it facilitates broader market access while ensuring that the food's provenance is not lost. Value chains are built on long-term interdependent relationships between all elements of the supply chain, from producer to retailer. These relationships ensure a dependable and predictable supply of product, while at the same time sharing risks, information and benefits for a more mutually beneficial and transparent arrangement than that found in conventional supply chains[24]. One of the greatest needs appears to be for brokers and distributors who will connect farmers with restaurants and retailers while maintaining traceability, transparency, profitability and trust. Partnerships among supply chain actors may also better coordinate product flow, helping to mitigate product supply and processing issues associated with seasonality. Studies from Europe suggest benefits to farmers and rural communities from short or alternative supply chains such as value chains[13,29,30]. Renting et al.[13] emphasize that these market opportunities 'result from the active construction of networks by various actors', and 'are not the result of some kind of external, elusive "free market"' (p. 399), suggesting the need for public and private sector engagement to achieve these benefits.

Conclusion

Effective consumer education and the concurrent development of direct and extended distribution channels can have a profound effect on farm viability and our food system in general. The re-embedding of food in nature and society, based on a set of shared values[18], changes the meaning of food, creating opportunity for citizenship and community where individuals express their values in the marketplace and take responsibility for the world around them through their purchase decisions. Certainly, no ecologically regenerative and socially just food and agriculture system is possible without well-informed, dedicated and conscientious consumers supporting it in the marketplace; while no one product or market can independently construct such a system, pasture-raised products appear to possess an appropriate mix of desired attributes to aid this re-embedding process.

Limitations and Future Directions

The interview findings reported in this paper are limited to the comments of the interviewees. The degree to which the interview findings can be generalized to other populations is unknown. Other key players in pasture-based livestock production, input suppliers, breeders, extension educators and other professionals, were not interviewed in this phase of the research.

In the survey portion, space limitations precluded the inclusion of questions on the importance of traditional demand drivers like price, and product quality (e.g. taste, appearance, tenderness, juiciness and safety). These attributes have been shown to be important in many studies and are a prerequisite for any marketable animal product.

As for future directions of research, this paper poses many questions, such as, given the competition in media for consumer attention, how can we most effectively communicate the values and attributes associated with pasture-based livestock production? What can we learn from past success stories of promotional efforts and distribution systems? How are value chains best governed? How can processing barriers be overcome? As farmers, processors, distributors and consumers come together to revitalize the food system, different departments and colleges at universities, including journalism, public relations, business, animal science, food science and agricultural economics, all have vital contributions to make.

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Soil property indices for assessing short-term changes in soil quality

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Abstract

Soil quality has been proposed as a prime indicator for characterizing and defining management factors contributing to soil degradation. In this study, biological (soil respiration, fluorescent *Pseudomonas* bacteria and entomopathogenic nematode populations), chemical (pH, inorganic N, and total C & N), and physical (bulk density and infiltration) indicators were used to determine soil quality. The specific research objective was to determine the capacity of this specific set of indicators to assess soil quality and determine its ability to detect short-term changes in soil conditions and processes. The assessment was comparative because of the lack of specific criteria or guidelines available in the literature for interpretation of most soil property indices measured. The following treatments were chosen from an ongoing farming systems study to achieve a preplanned set of comparisons that would make this type of assessment possible: (1) best management practices/ conventional tillage (BMP/CT), (2) BMP/no-tillage (BMP/NT), (3) an organic system, and (4) a successional fallow system. Assessments were made multiple times between 1999 and 2000. Statistical differences between systems were found for all soil quality indicators except for entomopathogenic nematodes. Differences between systems varied across dates, a result that supports other research stating the need to consider the temporal variability of these indices for an unbiased overall soil quality assessment. Differences in total carbon and total nitrogen between systems were most evident in the 2000 sampling dates with BMP/NT showing greater contents on the last sampling date. The soil pH and inorganic N results did not suggest a possible difference in soil function status between any of the three agricultural systems studied. All three agricultural systems, BMP/NT, BMP/CT and organic, had similar pH values and overall low soil inorganic N levels. The non-agricultural successional system had a slightly more acidic soil condition than the three agricultural systems. Soil bulk density increased with time in the untilled BMP/NT and successional systems but the resulting values were not considered detrimental to either productivity or environmental quality. Infiltration was lower in the BMP/NT and successional systems than in the BMP/CT and organic systems. In conclusion, all soil quality indicators except for entomopathogenic nematodes proved to be sensitive to the detection of rapid changes in soil conditions that occur by the influence of soil management. The importance of using soil bulk density to express soil results on a volume basis, as the soil exists in the field before sampling, prevented an average interpretation error of 7–14% as compared to treatment comparisons on a soil weight basis only. This also demonstrates the need to carefully consider field sampling locations (row, between row, or wheel traffic areas) which dramatically influence soil density, physical characteristics, organic matter concentrations, and biological activity. Failure to consider these factors can invalidate even the most careful approaches to establishing baseline soil quality levels in the field as affected by various tillage and residue management practices and associated comparisons in time.

Key words: large-scale systems research, multidisciplinary research, soil function, best management practices, no tillage, conventional tillage, organic

Introduction

US farmers are currently faced with a number of environmental issues, some of which include ground and surface water contamination, soil erosion, and declining soil quality[1]. Most farms rely on off-farm chemical inputs and have little resemblance to natural systems. Natural systems capture energy and nutrients through complex interactions, which are simplified and disrupted under agricultural uses[2]. Interactions between agricultural management practices and soil biological, chemical, and physical processes affect the productivity of agricultural soils and their impact on environmental quality[3].

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Table 1. Description of the three systems used for the soil quality assessment. These systems are part of the FSU, a long-term systems field experiment initiated in 1998 at the CEFS near Goldsboro, NC.

System	Subplot	Rotation	Characteristic
BMP	1. CT: chisel plowed + disked 2. No tillage (NT)	3-year corn–peanut–cotton with winter rye cover crop	Representative of farming systems in North Carolina and other southern states: annual crops, short rotations, and absence of animals.
Organic	None	3-year soybean–legume cover crop–sweet potato–legume cover–wheat/tomato	The focus of the initial rotation is on optimizing fertility and weed management for beginning organic producers whose goal is to transition to higher value crops.
Successional	None	None	Areas selected for this treatment have been allowed to succeed naturally since 1998, influenced only by natural processes.

The use of the term 'soil quality' is related to concepts of sustainability, particularly with regard to agricultural sustainability[4]. Soil quality is the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health[5]. The most distinctive contribution of soil quality research is an attempt to understand the linkages among management practices and systems, observable soil characteristics, soil processes and soil function[6].

Part of any system to evaluate the sustainability of farming practices requires identification of soil attributes that serve as indicators of change and also relate to productivity. Soil attributes that are sensitive to changes and perturbations in the soil environment can be used as indicators of the status or condition of a farm's resources[7]. The biologically active components of soil including organic matter, soil microbial biomass and energy sources such as organic C and N, are known to be sensitive indicators of changes in soil management[8]. Soil organisms play a major role in plant litter decomposition and nutrient cycling, but they also influence plant disease and protection[9] and provide biological control of soil-dwelling insect pests[10]. The overall focus of our research was to measure the effects of divergent agricultural practices on soil properties, with an interest on the sensitivity of these properties to capture rapid changes in soil conditions. The overall focus of our research was to measure the effects of divergent agricultural practices on soil properties, with an interest on the sensitivity of these properties to capture rapid changes in soil conditions. The specific research objective was to determine the capacity of a specific set of soil biological, chemical and physical properties to assess soil quality and determine its ability to detect short-term changes in soil conditions and processes.

Materials and Methods

Experimental site

The research site was the Farming Systems Unit (FSU) at the Center for Environmental Farming Systems (CEFS) near Goldsboro, NC (35°23′N, 78°5′W, elevation 35 m). The FSU is a large-scale long-term field experiment with a randomized complete block design having three replications and five farming systems. The systems that were sampled in this study are described in Table 1. They were a conventional system using best management practices (BMP), split into conventional tillage (CT) and no-tillage (NT) subplots, an organic production system and a successional ecosystem (old field succession). The FSU is approximately 80 ha in size with individual plots ranging from 0.81 to 4.05 ha. The dominant soil type within each replication is termed the diagnostic soil. The diagnostic soil types were Wickham sandy loam (fine-loamy, mixed, semiactive, thermic Typic Hapludult) and Tarboro loamy sand (mixed, thermic Typic Udipsamment). The site is blocked by soil type, such that all soil samples in a system are taken from the same 'diagnostic soil' in a given block.

The organic, BMP and the successional ecosystems were chosen for this study because they are most divergent with respect to management and therefore expected to experience short-term changes in soil quality. Soil chemical (pH, inorganic N, and total C and N), physical (bulk density and infiltration), and biological (soil respiration, entomopathogenic nematodes and *Pseudomonas* populations) indicators were measured.

Soil sampling

The study was initiated in September 1998 by planting rye (*Secale cereale* L.) on the entire 80 ha experimental site and systems were initiated in the spring of 1999. In March 1999, five random points were selected within each experimental plot for soil quality sampling. Following a baseline measurement, subsequent sampling was conducted over the course of the 1999 growing season, late May (spring) shortly after planting the summer crop (Summer I), mid-season at peak crop growth (Summer II), and post harvest in late October (fall). The same sampling cycle was repeated in the 2000 growing season. Each sampling site was physically marked and geo-referenced using a Trimble® backpack GPS unit and stored on a GIS database.

A composite of thirty, 2.54-cm diameter by 15-cm deep cores were taken adjacent to the plant row on the untracked side near the geo-referenced point. The composite samples were placed in large buckets lined with plastic bags and the soil thoroughly mixed by hand. The composite sample was then divided in the field into three equal portions of approximately 200 g for determination of pH, total C, total N, NO_3 and NH_4-N analyses and for quantifying entomopathogenic nematodes and fluorescent *Pseudomonas* populations.

Soil fertility indicators

Soil samples were prepared for testing by first air-drying and then fine grinding to pass through a 2-mm sieve. Soil pH was determined using a 1 : 1 soil to water ratio. For inorganic N (NH_4+NO_3-N) determinations, 5 g of air-dried, ground soil was weighed into a 50-ml plastic centrifuge tube. Fifty ml of a 1 M KCl solution was then added to the tube and the mixture shaken for 1 h. The tubes were then centrifuged at 1000 rpm for 12 min, after which time approximately 5 ml of the supernatant was transferred into plastic vials and frozen until further analysis. Samples were analyzed using a Latchat QuikChem Method 10-107-04-1-A and 10-17-05-A, for NH_4 and NO_3-N respectively. Total soil C and N were determined by combustion on a Perkin-Elmer 2400 CHN Elemental Analyzer.

Soil respiration and infiltration

The closed chamber method of Parkin et al.[11] was used to measure soil respiration *in situ* as an indirect measure of microbial activity. One measurement was made at each of the five plot geo-located points. A PVC ring 7.6 cm in diameter and 7.6 cm deep was forced 7.5 cm into the ground slightly to the side of the crop row on the untracked, inter-row side. Rings were installed after crop planting each year and remained in place for the multiple measurements made that year. To determine the headspace within each ring, the ring was lined with Saran Wrap and 2.54 cm of water added. The distance from the water surface to the top of the ring was measured. The Saran Wrap was then removed, allowing the water to drain into the soil within the ring. The ring was capped to be airtight. After 24 h, a 100-cm^3 gas sample was withdrawn from the closed chamber using a syringe and a Draeger® gas detector tube. This method actually calls for a one-half hour incubation time. Consequently the respiration results were conservative because the 24-h incubation time used in our study likely resulted in rates 2–4-fold lower than the standard assay (John Doran, personal communication 23 March, 2007). Headspace measurements were used to convert Draeger tube readings into kg C evolved ha^{-1} day^{-1}. The concentration of CO_2 gas was converted using the headspace volume in the chamber[11,12]. Another PVC ring 7.6 cm in diameter and 15 cm deep was installed just to the side of the crop row on the untracked inter-row side. These rings were installed after planting in the spring and remained in place for the duration of the cropping season. The elapsed time for the 2.54 cm of deionized water (non-constant head) to infiltrate the soil surface was recorded.

Bulk density

An Uhland core sampler[13] was used to obtain surface (upper 7.5-cm) bulk density on intact cores (7.6 cm in diameter by 7.6 cm in length) three times over the course of the two years, in March and November 1999, and November 2000. Measurements were taken in the crop row nearest the geo-referenced point.

Entomopathogenic nematodes and bacterial analyses

A 10-day *in vitro Galleria mellonella* bioassay was used to detect entomopathogenic nematodes in soil samples[14]. This method, which entails 'baiting' the sample with insect larvae and then searching for cadavers, is commonly called the *Galleria* bait method. The *G. mellonella* larvae are normally not exposed to nematodes and, therefore, are very susceptible to infection. Each plastic bag, which contained approximately 200 g of soil (taken from the larger composite sample), was baited with five *Galleria* larvae placed on the soil surface. The bags were sealed and incubated in the dark for five days. At the end of this time period, all five larvae were removed and the cause of death determined. The bags were then re-baited with five fresh larvae, incubated for an additional five days and a final determination made. The nematode family was determined by the color of the cadaver. An ocher color indicated the presence of *Xenorhabdus nematophila*, the associated bacterium of *Steinernema*, while red indicated the presence of *Photorhabdus luminescens*, the associated bacterium of *Heterorhabditis*. The cadavers were dissected if the infecting nematode species was uncertain.

Populations of fluorescent *Pseudomonas* bacteria were determined using the most probable number (MPN) technique[15] using a 96-well microtiter plate procedure[16] and 210 µl of liquid King's B medium[17] per well. The MPN of bacteria per gram of dry soil was determined using an Excel spreadsheet program[18].

Analyses of data

All chemical and biological measurements measured on a per soil weight basis were converted to a per soil volume basis using soil bulk density values. To satisfy the condition of homogeneity in the analysis of variance (ANOVA) some of the data were transformed as suggested by Gomez and Gomez[19]. The soil respiration, inorganic N and MPN data sets involved small values (e.g. less than 10) and were thus normalized with a logarithmic transformation of the form $\log(X+1)$, where X is the original data. A square root transformation of the form $(X+0.5)^{1/2}$ was used for the nematode data because of its small whole number nature and large presence of zeroes. All data were analyzed using SAS[20]

Table 2. Results from the ANOVA for the nine soil quality indicator properties measured.

Indicator	Source of variation			Coefficient of variation (%)
	System (S)	Date (D)	S × D	
Respiration	**	**	**	6.3
Bacterial numbers	NS	**	**	4.6
Nematode numbers	NS	**	NS	64.0
Inorganic N	*	**	**	20.5
Total carbon	NS	NS	*	22.8
Total nitrogen	NS	**	**	19.3
pH	NS	**	**	3.2
Bulk density	**	*	**	6.9
Infiltration	NS	**	NS	44.0

* and ** indicate significance at the 5 and 1% levels of probability, respectively. NS denotes non-significance.

following a split split-plot ANOVA model procedure and pair comparisons between systems using Tukey's test[21]. In the ANOVA, systems were treated as a whole plot factor, sub-system (e.g. BMP/NT and BMP/CT) as a subplot factor, and sampling date as a sub-sub plot factor. All statistical tests were interpreted at the 5% probability level.

Results

Results from the analysis of variance for each parameter indicator are shown in Table 2. In general, system responses differed by date of sampling for soil respiration, total inorganic N, total C, total N, soil pH and soil bulk density. Significant system and/or date of sampling main effects were found for the other parameters. The error variability in the data was high for entomopathogenic nematodes and infiltration time as indicated by the resulting coefficient of variations of 64.0 and 44.0%, respectively. Despite the magnitude of the error variance for these two parameters the date source of variation was highly significant in the analysis.

Biological indicators

Soil respiration rates were very low to moderately low ranging from 2.0 to 13.4 kg C ha^{-1} day^{-1} (Fig. 1). This was expected knowing that the site has a low carbon pool due to excessive tillage management prior to the study and the lack of time required to increase this pool under the newly implemented systems. Generally, summer respiration rates were lowest in the two tilled systems organic and BMP/CT and highest in the two un-tilled systems successional and BMP/NT. Some studies have shown that soil biological activity is enhanced in systems that minimize or eliminate tillage[22], while other studies have shown that no till and systems having similar characteristics mimic natural behavior unlike CT systems[23]. Several other studies have found a strong correlation between biological activity and degree of soil disturbance and amount of surface residue[7,22,24]. In general, undisturbed agronomic and natural environments have greater amounts of organic substrates for decomposer organisms[25]. The decomposing rye residue at the soil surface and the subsurface decomposition of the rye root mass likely contributed to the higher respiration rates in the successional and BMP/NT systems observed in the summer. In both years, respiration rates dropped from summer to fall to rates of 6.3 kg C ha^{-1} day^{-1} or below, mainly due to a decrease in soil temperature (temperature data not shown). Soil respiration rates were much higher in the summer of 2000 compared to 1999. This could be attributed to cooler temperatures and greater rainfall. It could also be that peanut, which provides a denser soil canopy compared to corn, provides an environment more conducive to microbial activity. As discussed earlier, the differences in soil respiration rates between treatments were likely conservative because of the 24-h incubation time used for this assay. Thus it is likely that the differences between treatments were even greater than we report here.

The three species of entomopathogenic nematodes detected were *Steinernema glaseri*, *Steinernema carpocapse* and *Heterorhabditis bacteriophora*. In general, *S. glaseri* nematodes were high in numbers while numbers for other species were low (Fig. 2). Characteristics of the *S. glaseri* species[26–29] that may explain its abundance include: (1) it is highly mobile and therefore effective at finding its insect host, (2) it survives well within a wide soil temperature range 15–35°C, and (3) it has been found to survive well in coarse textured soil because of better mobility through the large pore spaces.

Entomopathogenic nematodes are characterized based on foraging behaviors, with 'ambushers' being those that remain sedentary at or near the surface waiting for passing insect hosts, and 'cruisers', which are highly mobile and therefore can parasitize hosts with low mobility and reside within the soil profile[30]. *S. carpocapse*, an ambusher, has been shown to be highly sensitive to tillage and is likely to persist in undisturbed systems, which tend to have greater soil surface moisture and cooler temperatures[31]. The other two detected species are cruisers found to be less sensitive to tillage. Based on this, we expected to see greater numbers of *S. carpocapse* nematodes in the NT and successional systems and greater numbers of *S. glaseri* and

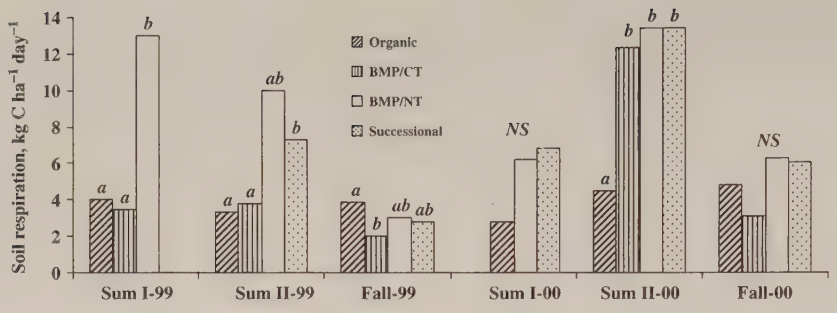

Figure 1. Soil respiration as measured by CO_2 evolution in the organic, BMP (NT and CT) and successional systems. Within each sampling date, means without a letter in common differ significantly at the 5% probability level. No significant difference between any two systems is denoted as NS.

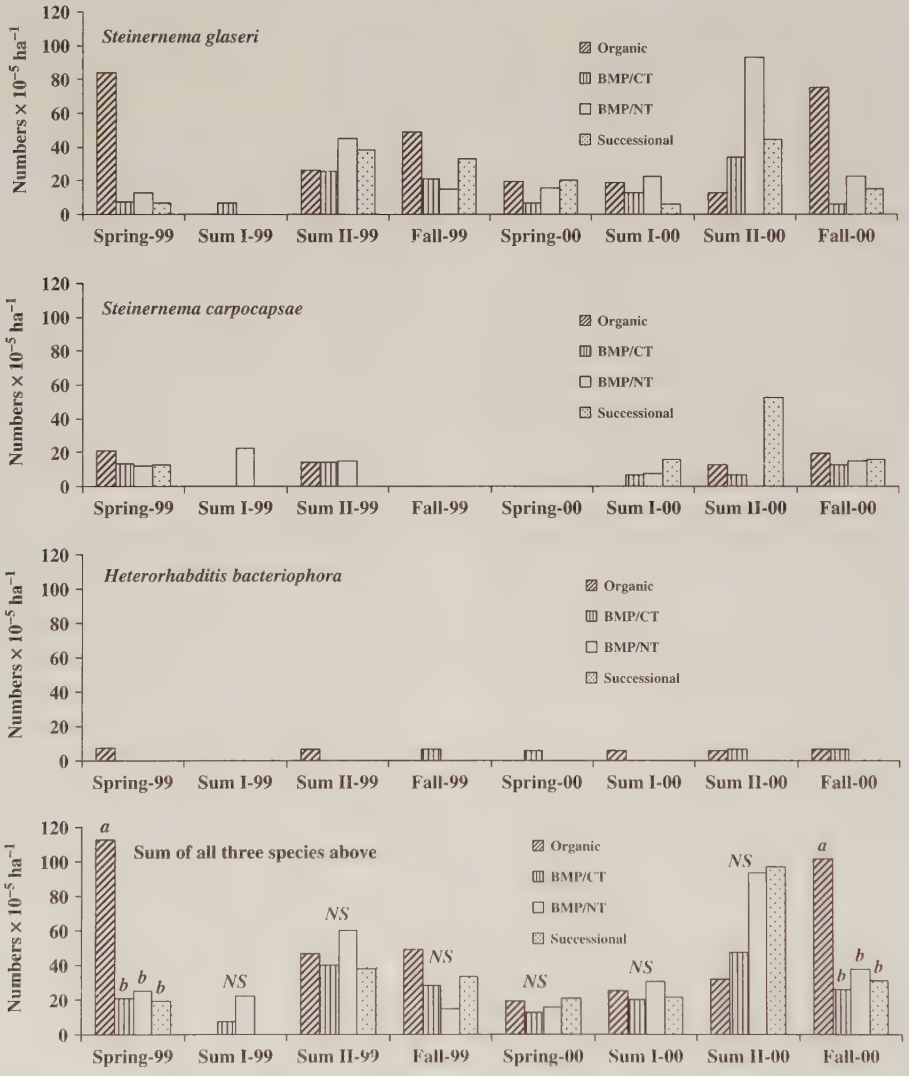

Figure 2. Nematode numbers at each sampling date in the organic, BMP (NT and CT) and successional systems. Within each sampling date, means without a letter in common differ significantly at the 5% probability level. No significant difference between any two systems is denoted as NS.

H. bacteriophora nematodes in the CT and organic systems. However, system differences in nematode numbers were found only on the spring 1999 and fall 2000 sampling events where the organic system showed significantly higher total nematode numbers than the other three systems. The higher numbers were due to an increase in the population of *S. glaseri* which we cannot explain.

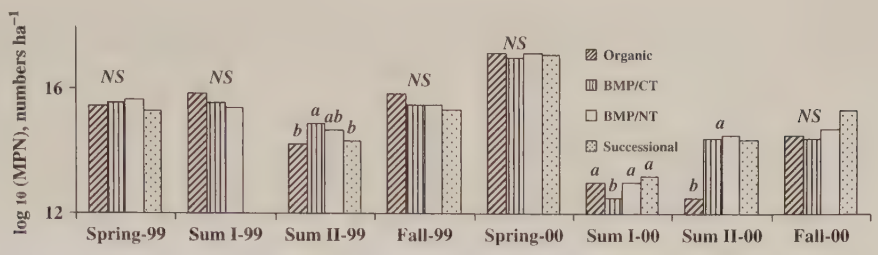

Figure 3. Bacterial numbers determined with the MPN technique at each sampling date in the organic, BMP (NT and CT) and successional systems. Within each sampling date, means without a letter in common differ significantly at the 5% probability level. No significant difference between any two systems is denoted as NS.

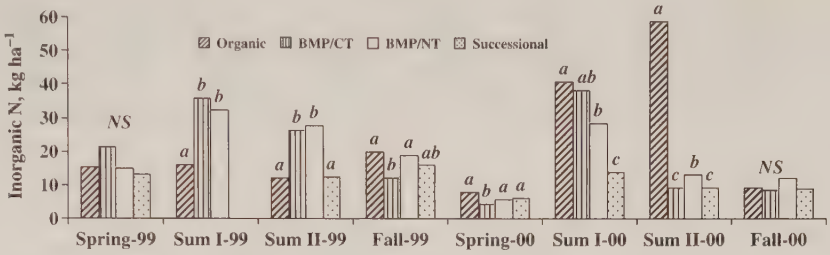

Figure 4. Total inorganic N (NO_3-N + NH_4-N) content in the upper 7.5 cm of soil for each sampling date in the organic, BMP (NT and CT) and successional systems. Within each sampling date, means without a letter in common differ significantly at the 5% probability level. No significant difference between any two systems is denoted as NS.

Bacterial numbers were generally higher in the spring and fall sampling dates and lowest in the summer sampling dates (Fig. 3). It has been shown that populations decrease into the summer months as a result of high soil temperatures and lower soil moisture[32]. Differences between systems were found in the second summer sampling date of 1999 and in both sampling dates in 2000. In 1999, numbers were slightly higher in the two BMP systems (NT and CT). In 2000, CT had fewer numbers for the first summer date and the organic system was lowest in number for the second summer date. The differences observed are likely due to a combination of factors including differences in soil moisture, crops grown, and types of surface residue, absence or presence of tillage, and use of agricultural chemicals.

Chemical indicators

Concentrations of NO_3-N and NH_4-N were determined separately, but NH_4-N values were small enough to be inconsequential, thus the NO_3^- and NH_4^+ data were pooled and results are reported as total inorganic N (Fig. 4). Inorganic N contents were low overall but some system differences did occur. The differences occurred mainly in the summer and were due to differences in fertilizer applications. A corn crop was planted in the BMP systems in 1999 and fertilized with 30% urea ammonium nitrate (UAN) once in April at a rate of 14 kg N ha^{-1} and again in June at a rate of 132 kg N ha^{-1}. This explains the greater inorganic N contents found in the BMP systems in the two summer 1999 sampling dates. This was also observed in the summer sampling dates of 2000. The high inorganic N contents found in the organic system in the summer dates of 2000 likely resulted from a turkey litter incorporation of 4.5 Mg ha^{-1} made on May 5.

Soil total carbon and total nitrogen contents in each system varied with time (Fig. 5). These two properties did not differ between systems until fall 1999 where the untilled BMP/NT and successional systems began to show slightly higher levels than the tilled BMP/CT and organic systems. Differences between these two system groups (untilled versus tilled) became more evident in 2000. NT had the highest carbon and nitrogen content on the last sampling date (fall 2000).

We did not expect to find differences in soil carbon and nitrogen content at this early stage in the development of these systems. Many studies have reported changes with time over the long term (10+ years)[7,33,34], while few studies have found differences over short terms[35].

In general, most studies agree in that tillage stimulates the decomposition of organic matter resulting in a net decline in content with time. The incorporation of organic matter into the plow layer generally exposes organic matter to higher soil moisture content than at the soil surface and therefore leads to greater decomposition[36].

Because conservation tillage systems like NT leave residues near or at the soil surface, most investigations report a substantial change in soil organic matter in surface soil as compared with CT systems. It is also known that soil organic matter is sorbed on the surfaces of the fine mineral particles to form microaggregates and in this way is protected from microbial decomposition[37]. Tillage breaks aggregates apart making this organic matter available to soil microbes and therefore stimulates the decomposition process.

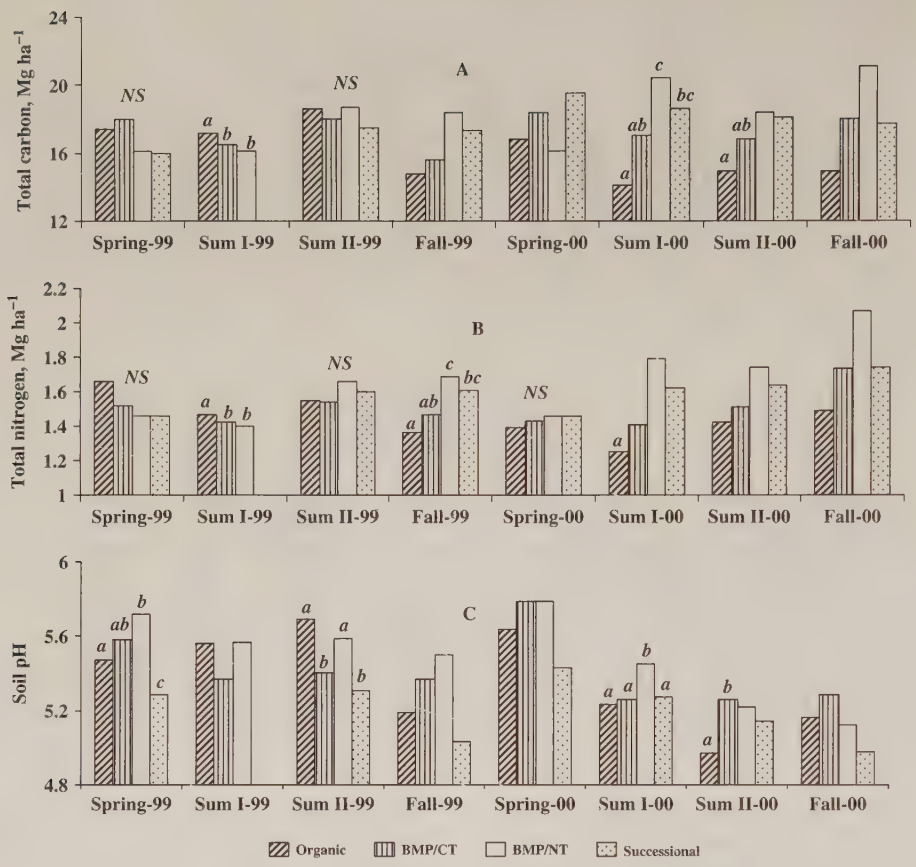

Figure 5. Soil total carbon (A), total N (B) and pH (C) at each sampling date in the organic, BMP (NT and CT) and successional systems. Within each sampling date, means without a letter in common differ significantly at the 5% probability level. NS is non-significant.

Another factor affecting the dynamics of carbon and nitrogen in the untilled systems group (BMP/NT and successional) is the frequent wetting and drying at the soil surface. The slower decomposition of residue during dry periods decreases net losses of carbon by microbial consumption and thus favors the sequestration process. On the other hand, the frequent wetting and drying has been found to increase the resistance of certain N compounds to microbial decomposition which leads to higher total N accumulation in the surface[36].

Soil pH values ranged between 5.0 and 5.7 indicating moderately acid (pH 6.0–5.5) to strongly acid (pH 5.5–5.0) conditions (Fig. 5). Values from spring to fall in 1999 were somewhat consistent for the agronomic systems for organic, BMP/CT and BMP/NT. The successional system was different having a lower pH on each sampling date and also the pH decreased from spring to fall. Interestingly, the pH for all systems increased from fall 1999 to spring 2000. The same trend as in 1999 was observed in 2000 with the successional system having a lower pH on each sampling date but this year all four systems showed a decrease in pH from spring to fall.

The difference in acidity between the successional system and the other systems is likely related to differences in organic matter dynamics and microbial activities. The highly diverse group of broadleaf plants and grasses that grew in the successional system produced large amounts of plant biomass and thatch residue. The decomposition of this residue releases acid functional groups from which H^+ ions dissociate. Also, the increase in residue biomass with time likely stimulated microbial activity and therefore increased the production of carbonic acid, a by-product from microbial respiration. This is supported by the observation that soil pH increased in the successional system from fall 1999 to spring 2000. During this period microbial activity is at its lowest because of low soil temperatures and therefore the production of carbonic acid is likely at its minimum. The successional system is also characterized by having grass species with massive root systems. Thus, a significant amount of carbonic acid is likely being produced as a by-product from root respiration.

Physical indicators

No differences in soil bulk density were found between systems in spring 1999 (Table 3). Averaged across systems, the bulk density was 1.36 g cm^{-3} on this base-line sampling date. With time, values remained at or below 1.36 g cm^{-3} in the tilled organic and BMP/CT systems and increased to higher levels in the untilled successional and BMP/NT systems. The increase in bulk density in the untilled systems characterizes the magnitude of natural settling and

Table 3. Soil bulk density and infiltration at each sampling date in the organic, BMP (NT and CT) and successional systems.

	Bulk density ($g\,cm^{-3}$)			
Sampling date	**Organic**	**BMP/CT**	**BMP/NT**	**Successional**
Spring-99	1.38a	1.36a	1.36a	1.34a
Fall-99	1.35a	1.36a	1.47b	1.44b
Fall-00	1.28a	1.32a	1.53b	1.48b
		Infiltration ($cm\,h^{-1}$)		
Sum I-99	245.3a	184.0a	81.8b	ND[1]
Sum II-99	109.8a	44.7b	33.5b	72.5ab
Fall-99	59.5a	62.3a	48.8a	103.9a
Sum I-00	ND[1]	114.6a	16.3b	48.3b
Sum II-00	22.6a	45.2a	6.5a	31.2a
Fall-00	94.0a	78.9ab	17.2b	40.4ab

[1] ND, not determined.
Within each sampling date, means without a letter in common differ significantly at the 5% probability level.

consolidation that occurred with time. In general, the natural settling of soil that occurred from fall 1999 to fall 2000 increased the bulk density of the untilled systems from $1.36\,g\,cm^{-3}$ to $1.50\,g\,cm^{-3}$ on the average. This final bulk density is below the critical root limiting value of $1.60\,g\,cm^{-3}$ identified in the scientific literature[38] for the soil type found at the study site. However, the differences in treatments observed demonstrate the importance of using bulk density to adjust soil analysis to a volume basis (see Doran and Parkin[3], p. 29–32). The bulk densities of successional and BMP/NT systems averaged 7.3 and 14% higher than those of the organic and BMP/CT systems in fall of 1999 and 2000, respectively (Table 3). Thus, failure to adjust soil analysis (including microbial counts) from a weight to a volume basis would have resulted in an average error of interpretation of treatment comparisons in the field of from 7 to 14%—an unacceptable error by any standards.

Despite the large error variability in the infiltration data, differences between systems were found in most sampling dates (Table 3). The general trend in the data fits well with the soil bulk density data in that the two untilled systems BMP/NT and successional had higher bulk densities and lower infiltration rates. Also, the tilled BMP/CT and organic systems had lower bulk densities and higher infiltration rates. These trends were most evident in the fall 2000 date. In general, comparing the infiltration rate average between the two tillage groups (tilled versus untilled) in fall 2000 reveals that the consolidated state of soil in the untilled systems decreased infiltration by $48.2\,cm\,h^{-1}$.

Measurements of infiltration using ring or cylinder techniques[39] can be naturally highly variable but there are some sources of variability that can be controlled. Since the movement of water in soil is determined by the nature of the soil matrix, any factors affecting porosity and pore-size distribution should be considered when choosing areas to be sampled. For example, wheel-trafficked areas, highly washed or eroded zones, and foot-trafficked locations should be avoided when sampling. However, wheel track areas should be assessed separately if they critically influence the characteristics of runoff, infiltration, and potential erosion from a field. Also, physical properties have been shown to vary with distance from crop rows for various reasons[40]. Therefore, it is important to sample the same plot location using the crop row as a reference point.

Discussion

A resourceful soil quality assessment includes measurements of physical, chemical and biological properties that reflect the status of the multiple soil functions affecting productivity and environmental health[41]. With this in mind, we measured soil properties that relate to critical soil functions in agricultural systems in the Atlantic Coastal Plains region. For example, excessive tillage has degraded soil properties and resulted in productivity losses in many cases. Adverse soil conditions resulting from inadequate soil management include: (1) compacted soil zones that restrict crop rooting and water movement[42], (2) systems with low biological activity because of depleted soil organic matter or the system's limited ability to accumulate organic matter[43], and (3) increased soil acidity and high exchangeable aluminum[44]. The soil quality assessment must also consider temporal and spatial variations of these functions[45]. We therefore measured the soil properties collectively and at the same field locations over time.

At this early stage of this long-term study, statistical differences between systems were found for all soil quality indicators except for entomopathogenic nematodes. For most indicators, the error variances in the statistical analyses were low, indicating that sample numbers were adequate. The nature of system response varied from sampling date to sampling date for most properties. This differential response emphasizes the importance of multiple sampling when evaluating soil quality and when making comparative system evaluations.

The biological assessment was emphasized by including not only soil respiration measurements but also populations of beneficial soil bacteria and entomopathogenic nematodes. We believe these organisms contribute to the overall health of the soil ecosystem because of their link to disease suppressive soils and parasitism of plant pests. At this early stage it is difficult to conclude that these parameters are sensitive to soil management. It is our hope that these measurements become useful as a survey of endemic populations at this early stage and as a base-line point in an expected long-term differential response.

The soil respiration data indicated higher microbial activity in the BMP/NT and successional untilled systems. As discussed earlier, these differences would likely have been 2–4 fold higher had a half-hour respiration incubation time been used. While this *in situ*, simple and relatively fast method of evaluating CO_2 efflux proved to be system-sensitive, it has no way to differentiate between efflux from root respiration and efflux from microbial respiration. Also, the method does not provide for a standard or critical level that can be used to determine how much CO_2 evolved is 'good' or excessive, or results in a net loss of carbon from the system.

Like the biological data, the chemical data (total C, total N, soil pH and inorganic N) was sensitive to system management. For total C and N, differences between systems were most evident in the 2000 sampling dates, with BMP/NT showing greater contents on the last sampling date. The soil pH and inorganic N results do not suggest a possible difference in soil function status between any two of the agricultural systems studied. All three agricultural systems, BMP/NT, BMP/CT and organic, had similar pH values and overall low soil inorganic N levels. The successional system had a slightly more acidic soil condition than the three other systems.

Soil bulk density increased with time in the untilled BMP/NT and successional systems but the resulting values were not considered detrimental to either productivity or environmental quality. The magnitude of difference in bulk density between the two tilled BMP/CT and organic systems and the two untilled BMP/NT and successional systems accents the importance of expressing the results of soil quality indices on a volumetric rather than a gravimetric basis. By fall 2000, these two system groups differed in bulk density by $0.20\,g\,cm^{-3}$, a difference that results in the calculated volumetric index value being 15% greater in the untilled systems relative to the tilled systems.

The infiltration measurements were highly variable but the system effect was large in magnitude on some sampling dates and therefore significant in the statistical analysis. It is important to avoid added variability with this measurement by choosing appropriate sampling locations that represent overall field conditions. For example, disturbed areas by vehicular or foot traffic or eroded or highly washed areas that do not represent the overall surface of the system being evaluated should be avoided.

In conclusion, most soil quality indicators proved to be sensitive to the detection of rapid changes in soil conditions that occur by the influence of soil management. The results fulfill the first phase of the long-term soil quality assessment being conducted at the experimental site; to document the soil conditions of the systems at their inception. The soil quality indicators will be measured multiple times in the next several years to monitor temporal changes in soil function. The base-line information generated in this study and the long-term monitoring of the systems will be used to evaluate the amount, direction, and speed of change in soil quality and resulting impacts on crop productivity and the environment.

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Integrated crop/livestock systems research: Practical research considerations

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Abstract

There are many reasons for the paucity of integrated crop/livestock research and associated publications. Integrated/crop livestock experiments that involve adequate treatments and replications, as perceived by both crop and animal scientists, require large numbers of hectares, many animals, considerable labor to conduct the research, substantial financial resources, and a commitment by Federal and State Research Agencies to fund such long-term research projects. To be truly integrated, crop/livestock research must be multidisciplinary, involving scientists of diverse training and experience with expertise to address various aspects of the research problem, and scientists must function as a cohesive unit or team. The prevailing attitude that all experimental data must be statistically analyzed to be of any value is also a detriment to integrated research. Statistical analyses of these projects may be quite challenging and require new or unusual approaches. Related to the prevailing need for statistical analysis is also the need for scientists to publish senior authored publications for career advancement. Conducting integrated research may not facilitate scientists' publishing the number and quality of publications required for them to meet these criteria. A further obstacle to integrated research alluded to above, involves the many experimental design compromises that must be made by cooperating scientists. Crop and soil scientists for example, use many treatments and replications with small plots, while animal scientists, by necessity, have experiments that involve relatively large numbers of hectares and animal numbers with relatively few treatments and replications. It is therefore extremely difficult to initiate such projects given these inherent differences in crop versus livestock research protocol, as well as to design effective experiments that will provide publishable data. Making compromises on the many factors relevant to integrated crop/livestock research while designing experiments that will provide solutions to pertinent producer problems as well as useful data that can be statistically analyzed and published is, therefore, extremely difficult.

Key words: integrated crop/livestock systems

Introduction

During the 1980s and 1990s, there were discussions suggesting that reintegrating crop and livestock enterprises was essential to a more sustainable agriculture. Several philosophical papers have been published on this concept[1–4], as well as papers expressing the need for integrated crop/livestock research[5–9].

Since World War II, there has been a general trend in North America for declining crop diversity and a concentration of research funding on a few selected crops such as corn (*Zea mays* L.), soybeans [*Glycine max* (L.) Merr.] and wheat (*Triticum aestivum* L.)[4]. Many farmers are now producing only one or two crops[6], and there is mounting evidence that this approach is neither profitable for producers nor good for the environment[9]. More complementary production systems need to be developed that include both crops and livestock, and facilitate more efficient nutrient cycling systems, with the option of marketing farm-raised agricultural grain and forages through livestock[4]. An ecological rather than a factory approach to agriculture is needed for sustainable agricultural systems[7]. In the future, new technologies will have to conform to the environments where they are used, not dominate them[8]. There is a need for more sustainable agricultural production systems that reduce production costs by minimizing the use of purchased inputs such as fertilizers and pesticides, while decreasing adverse environmental effects[1,5]. Design of well-planned cropping systems that include legumes, with crops established by no-till seeding procedures, and where part or all of the grain is marketed through farm produced livestock should

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facilitate development of the unique and innovative production systems needed to make farms more profitable and sustainable[1,10,11].

Despite much discussion and debate over the value of, and the need for integrated crop/livestock research, little research has actually been conducted and published on this subject. Most 'integrated' research has occurred in Europe and involves only crop production, where the use of crop rotations and a less intensive management system have been successfully employed to reduce fertilizer and pesticide inputs[12,13]. In a survey of research projects described by their authors as sustainable, only 25% involved both crops and livestock[14].

Literature on interdisciplinary research that integrates crops and livestock are meager. Our review of the literature found three examples of crop/livestock systems that were truly integrated. The first was an interdisciplinary research project integrating both crop and livestock in a whole farm system initiated in southwest Virginia, USA in 1988[15]. The second was in Syria where a model farm approach using three farm types was employed to investigate the benefits of closer crop/livestock integration and to determine which farm type best enhanced sheep production[16]. In North Dakota, USA an integrated crop/livestock project was designed to reduce fertilizer and pesticide inputs through the use of crop rotations, polyculture and stand density[11]. This system was designed to produce crops, in a cropping system, that could be used for on-site winter grazing to reduce winter feed costs of dry, pregnant beef cows[10]. These three research programs overcame a number of obstacles and paradigms to publish their results.

The purpose of this review is to focus on some possible considerations or reasons why there have been relatively few integrated crop/livestock research programs, and even fewer publications in the past two to three decades.

Terminology

One reason for the dearth of integrated crop/livestock research can be traced to the terminology used to describe this research and the way it is perceived by many scientists. Without a better understanding of popular terminology and establishment of clear philosophical goals, it will be impossible to design and conduct relevant crop/livestock research. Some terms and concepts associated with integrating crop and livestock production that are not universally accepted by scientists in a positive way include: sustainability, alternative agriculture[17], organic farming[18], low-input sustainable agriculture (LISA), reduced-input agriculture[19] and the perception that alternative agriculture is a return to low-tech production methods of the past[20]. Some have proposed that sustainability encompasses food security, environmental concern and economic equity[21]. Keeney[1] suggested the following working definition of 'sustainability': 'agricultural systems that are environmentally sound, profitable, and productive and that maintain the social fabric of the rural community'. Keeney[1] indicated that key components of sustainability include, soil erosion control, pest management, efficient use of on-farm and purchased inputs, maintenance of soil fertility, and utilization of biological principles in the farming operation. Pretty[22] cautioned that sustainable agriculture should not be described in 'a concretely defined set of technologies, practices or policies that would restrict the future options of farmers'. 'Regenerative' agriculture has been suggested as a more descriptive and therefore, perhaps a more acceptable term than 'alternative' agriculture[5]. Sustainability involves greater reliance on renewable resources while protecting our environment from degradation[14].

Facility requirements

Integrated crop/livestock research that encompasses a desirable number of crop and animal treatments and replications would require a large number of hectares, considerable labor, and prodigious budgets to facilitate statistical analyses by conventional procedures and to provide meaningful information for producers. Such extensive research would require a high degree of on-site management and would result in complicated interactions that would be difficult to interpret. Most scientists are accustomed to operating on government or university research facilities in a rather controlled environment that may be more like a laboratory than the real world[23]. Scientific knowledge developed in such environments is usually thought to be superior to knowledge developed on producer's farms[24]. However, this has led some to the observation that agricultural research results are not broadly applicable and may not be relevant for the complete range of conditions that occur, even in a given locale[7].

It has been suggested that more research needs to be carried out on farms and under farm conditions so that the results will be more applicable to producer needs[8]. Conducting integrated crop/livestock research on producer farms would provide the extensive land and labor resources needed to conduct integrated crop/livestock research, but this approach also presents other concerns for scientists. Producers may not have an adequate appreciation for accepted research practices and thus may not realize the necessity of closely following the research protocol. Producers may elect not to adhere strictly to experimental protocol in order to prevent or avoid economic losses or damage that could reduce productivity of crops or livestock, if experimental treatments were strictly followed. Producers may alter protocol without consulting scientists because of convenience, the perception that treatments are not working or carelessness. These changes can diminish the value of research results and compromise their interpretation without the scientist even being aware of the situation. On the positive side, the need for multiple crop/livestock treatments with multiple replications make individual farms an ideal means of fulfilling both of these needs, assuming there is adequate cooperation among producers and scientists so that non-experimental variables

can be similarly controlled on cooperating farms. On-farm research not only provides much needed research information, but also provides practical cutting edge research that has direct impact to the producer. An example of farms serving as replications is in central Illinois, USA, where researchers and producers have been collaborating on different aspects of sustainable agriculture systems[25]. Farmers were selected from northern, central and southern Illinois to include cover crops in their cropping systems to improve efficiency and profit. Results indicated cover crops were promising in southern Illinois and added to the agricultural sustainability, but were not sustainable in northern Illinois.

Cropping systems used in integrated crop/livestock experiments need to be designed around the number of animals being used and their specific class and type, in order to ensure that an adequate supply of feed will be available to maintain the desired animal condition during the planned feeding period. The need to accommodate animal needs necessitates the use of experimental plots that are much larger than normally used by agronomists and soil and crop scientists. Use of larger plots may require compromises in experimental design necessitating the use of unique statistical approaches. The prevailing view that all research results must be subjected to rigorous statistical analyses may discourage some scientists from becoming involved in research that cannot be easily analyzed[6]. Karn *et al.*[10] and Tanaka *et al.*[11] illustrate how they had to compromise to conduct integrated crop/livestock research. They had to increase plot size, reduce agronomic soil and crop treatments, and use unbalanced treatment replications to provide adequate forage for the number of livestock needed to conduct the livestock research. The animal portion of the research had to be maintained longer than required in order to facilitate collection of publishable crop and soil research.

Scientific cooperation obstacles

To be truly integrated, crop/livestock research must be multidisciplinary, involving scientists of diverse training and experience with expertise to address different aspects of a research problem, and scientists must function as a team. For scientists to work as a team, individuals must set aside personal priorities for the benefit of the group. The need for a team approach also implies that individual scientists will labor in relative anonymity[6]. One problem with this ideal is that responsibilities, research costs, and workloads of team members will likely differ substantially, with the scientists responsible for maintaining the crops and livestock having a disproportionately larger workload and research cost than scientists who only collect and analyze data from an ongoing experiment. Scientists with the least responsibility in an integrated crop/livestock project may have the same or even a greater opportunity to publish, compared with scientists who have the most responsibilities. If the team interaction necessary for integrated crop/livestock research is to flourish, then administrators need to adequately address these inequities. One potential way to reduce some of the inequalities is to establish something similar to a principle investigator approach, which may help to provide credit to team members with the most responsibility, research cost and workload[8].

The team must formulate the problem, often the most difficult aspect of multidisciplinary research[26]. Appropriate data to be collected must be agreed upon, and there must be agreement on which individuals will be responsible for maintaining experimental plots and animals, as well as those that will collect and analyze data. Scientists must be willing to assist each other with peak workload duties as needed. Expected manuscripts and individuals responsible for authoring those manuscripts should be agreed upon before research is initiated.

Team research is also more difficult, because data collection requirements of all scientists must be considered before any actions are taken that could compromise other scientists' data collection. When scientists are working alone, many of these concerns do not exist. Cooperation in integrated crop/livestock research can also compromise an individual scientist's freedom to conduct research where the best facilities are available, where labor is easily accessible and where extraneous effects that could impact experimental outcomes can be controlled. Therefore, team research is much more difficult to conduct and interpret than an individual scientist's research, but team research provides information on the interactions of a problem rather than one component of the problem. Administrations and funding agencies must realize that to conduct integrated crop/livestock research involving multidisciplinary teams solving multiple-interaction problems requires greater funding resources and communications among scientists. Funding and communication may be the greatest deterrent to multidisciplinary teams and integrated crop/livestock research.

Academic training received by agronomists, soil and crop and animal scientists is generally quite focused for each specialty area, and scientists within these specialty areas develop their own technical jargon which can hamper communication with scientists in another discipline. Scientists usually work within a specialty area with like-minded individuals who generally understand each other's requirements, problems and needs. There is a risk in moving out of that comfort zone to unfamiliar, untested areas.

Traditionally designed experiments have a limited scope so they can be easily analyzed and readily interpreted, while the interactions in integrated crop/livestock research may be more important than crop or livestock treatments alone. Soil and crop scientists and agronomists generally use many treatments and replications with relatively small plot areas. Animal scientists, on the other hand, use relatively large numbers of animals and extensive land areas per treatment, which usually results in treatments and replications being limited. This fundamental difference

alone makes design of integrated crop/livestock research difficult, because each discipline area has valid reasons for their experimental design. Tanaka *et al.*[11] have suggested that changes in crops and soils in the northern Great Plains are slow, and their research indicates that 4 years of research data may not be adequate to understand the interactions among cropping systems and livestock on forage and grain production.

Integrated crop/livestock research is long-term in nature. Relative to time and resource requirements, the publication output initially may be low and may be orientated towards publications that accept applied research, with basic process-driven research published later. These initial applied research publications may not be looked on favorably by some administrators and scientists and may retard a scientist's academic advancement because of short-term implications. Evaluation of scientists as individuals rather than as a team, discourages an unselfish multi-disciplinary team approach at the expense of enhancing the knowledge base of very complex problems associated with integrated crop/livestock production.

The pressure to publish is one of the biggest obstacles to integrated crop/livestock research. Scientists, by academic necessity must conduct research that leads to senior authored publications. In describing the institutional development cycle, Axinn[27] observed that excessive specialization by scientists leads to severe communication problems and diminished collaboration with scientists in other disciplines. Further evidence of this trend in communication and collaboration problems is the current emphasis on journal articles rather than the scientist's participation in development and adoption of team oriented technology as a criterion for professional development[27]. A subtle indicator of this trend is that research has been designed to have a high probability of statistical differences, for publication purposes, rather than practical significance to solving pertinent producer problems. Hence, the clientele group for many scientists has become their own peers.

The major dilemma facing scientists, therefore, which discourages initiation of and participation in integrated crop/livestock research, is the pressure to satisfy the often short-term requirement of producing sufficient publications in contrast to the long-term commitment demanded by this type of research. Usually working within an institutional setting, scientists are under the mandate to solve real problems affecting the institution's stakeholders. Given this mandate, they struggle to design experiments that attempt to address these problems (which are usually quite complex) in the long-term, but will also hopefully render statistically significant data in the short-term for publishing. Often these two goals are not compatible[8]. Most scientists feel the use of statistics is necessary to validate experiments[6]. Grierson[28] concluded that many investigations in biological sciences are not suited to statistically designed experiments, and the pressure to use statistics discourages some scientists from tackling these difficult problems, since the statistics is not intuitively obvious. Over-emphasis on the use of statistical significance to validate experiments is therefore a detriment to integrated crop/livestock research. Also, the relationship between biological data and economic data is not always clear. Nonsignficance in the former does not imply the same in the latter; therefore, exclusive reliance on statistical significance may result in economically significant results being ignored[29]. Biological statistical significance does not necessarily equate to economic statistical significance at a given point in time. The dynamics of integrated crop/livestock systems can be altered by changes in commodity value, weather, and technology.

Cropping system decisions

By necessity, there are practical limitations to the scope of a cropping system that is part of an integrated crop/livestock project. Crop and soil scientists must consider many questions as they design the cropping systems portion of an integrated project. Their first task is to determine the research goals of the cropping system. Possible goals may include enhancing long-term production sustainability, maximizing farm income, reducing herbicide or pesticide use, reducing chemical fertilizer use, improving soil quality, improving water-use efficiency, filling forage quality and quantity deficits at a given time during the year for a particular type and class of animal, or a combination of these goals. Crops and crop sequences play a critical role in the sustainability of cropping systems[30]. After the cropping system goals are determined, scientists must decide what tillage methods will be used to produce the crops and make efficient use of precipitation. Tillage options include conventional tillage, minimum tillage and no tillage or some practical combination of these options.

Early in the planning process, scientists must decide how many treatments (crops) and replications they can accommodate. From all of the possible crops that can be grown in a given climatic region, scientists must decide which crops are most likely to thrive and be economically feasible under an integrated production system.

Scientists must decide whether annual crops, perennial crops or a combination of annual and perennial crops would work best. It is critical to agree on the function that each crop will have in the system, whether it is for animal feed, soil enhancement or cash sale. Grasses, legumes, or oil seed crops could be used for forage production or as cash crops in an integrated system. Researchers must decide whether to use crops that are well established in a given climatic region, or to try novel crops that are new and untested in addition to native or introduced forages. After deciding which crops will be used, the specific varieties or cultivars must be determined. Established varieties may be appropriate, but it may be desirable to incorporate relatively new genetic material. Both warm- and cool-season species may be desirable to facilitate weed control, or perhaps to maintain a continuous season-long supply of high-quality

Table 1. Some potential key issues to consider when addressing integrated crop/livestock systems research, based on Tanaka *et al.*[11] and Karn *et al.*[10].

Crop issues	Livestock issues
• Relevance and goal of cropping system • Land resources available (plot size) • Cropping system sustainability • Cover crop use and goals • Crop diversity in time and space (species and variety) • Multiple uses of crops • Crop management practices and environmental awareness • Reduced reliance on fossil fuel inputs • Quality and quantity of grain and forage for livestock during critical feeding periods • Efficient precipitation use by cropping system • Soil and water resource influences from livestock • Experimental design and statistical analysis of cropping system treatments • Variables to be measured (crop and soil) • Length of time research will be conducted • Authorship and publications	• Relevance and goal of livestock • Class, size and type of livestock (species and breed) • Critical feed periods • Animal performance • Land resources to produce sustainable forage or grain for livestock • Livestock number • Livestock feeding system (grazing: standing or swath; or confined in the corral) • Water and shelter access • Experimental design and statistical analysis of livestock treatments • Variables to be measured (frequency, time, number, etc.) • Authorship and publications

forage for livestock. The intent of the crops in the cropping system will help determine which crops should be used, and whether they should be seeded as monocultures or polycultures. Integrated systems could include crop diversity in both time (rotations), and space (polyculture). Polyculture systems provide greater plant diversity and enhance soil microbial diversity and such systems are able to take advantage of erratic precipitation frequency and distribution during the growing season. Selected crops must be multifunctional, they must provide forage or grain for livestock in the system and/or be used for cash sale. But, they must also facilitate the maintenance of soil health and fertility, by fixing nitrogen, providing crop residue for erosion control and soil water conservation, or facilitating management of weed, disease, and insect problems.

If selected crops are for use in a rotation, the rotation length, the function of the crops in the rotation and the number of cycles the rotation will be maintained are critical decisions. Forage crops may either be harvested for use elsewhere or grazed on site. Forages grazed on site may either be grazed standing or swathed for use during another season of the year. Crop quality factors will be determined by time of use, crop selection, and seeding and harvest date.

One final consideration for a cropping system might be whether it is desirable to enhance or reduce wildlife production. Enhancing wildlife numbers could be either good or bad depending on the goals of producers using a cropping system.

Livestock decisions

Concurrently with cropping system decisions, scientists must determine the goals and objectives of the animal portion of an integrated crop/livestock project. Possible goals include optimizing farm income by marketing all or a portion of the grain through livestock; using animals to consume forages or low quality grains that might otherwise be wasted or of low economic value, enhancement of soil quality, and reduction of harvesting costs by maintaining animals on crop production sites where crop residues can be utilized and animal wastes retained on the soil. A secondary goal might be to use only feeds produced in the crop portion of an integrated crop/livestock system, versus including limited quantities of purchased feeds to optimize animal performance.

After goals for the animal portion of an integrated crop/livestock project are determined, scientists must decide which animal species would best facilitate reaching those goals. Depending on the goals of an integrated crop/livestock system, cattle, sheep, swine, poultry, exotic animals such as bison, deer, elk, or a combination of animal species could be used as the animal component. Ruminants can utilize low quality forages while swine and poultry are good grain scavengers. If more than one animal species are used, the scope of the project and demands on the crops portion of the project will be substantially increased. After deciding on the animal species to be used, it must be determined whether breeding animals, growing and finishing animals or some combination will be used, because the age, sex and stage of animal production, along with the time forages are used, will help determine the amount and quality of feed needed from the cropping system side of the project.

If domestic livestock species are to be used, scientists must decide which breeds have the greatest potential for the system. Breed considerations involve choosing animals that have some characteristic or characteristics that would be advantageous in the proposed integrated system versus animals that are locally adapted and/or locally preferred. Whether traditional or innovative new animal management

procedures are used, cropping systems must supply adequate feed or supplement diet for the required number of animals over an extended time period. One of the most difficult decisions in an integrated crop/livestock research project involves crop plot size. Plots must be large enough to produce the amount of feed required to sustain the number of animals needed to collect valid animal data, but small enough to minimize crop production variability. Larger plots mean more work and likely an unfamiliar experimental design for crop scientists. Both crop and animal scientists will need to compromise on this critical issue. Some of the potential issues for scientists to consider prior to integrated crop/livestock research are listed in Table 1. A reasonable compromise must be reached which will provide viable data to both crop and animal scientists. Tanaka *et al.*[11] and Karn *et al.*[10] provide an example of the compromise needed when conducting integrated crop/livestock research.

Summary

Over the decades, agriculture has evolved into a number of differentiated forms. Agricultural producers have become more specialized and focused, which has caused larger economic scale and resulted in the uncoupling of many crop and livestock production enterprises. In the future, diversity provides the key to overcoming many problems associated with monoculture in cropping systems, and along with combinations of livestock can help to ensure a productive and profitable agriculture. One way of increasing diversity in agricultural systems is through integration of crops and livestock. Many resulting integrated crop/livestock operations of producers may not be as large in scale as crop or livestock systems alone, but integrated crop/livestock systems will spread the risk over more enterprises, may be more efficient in their use of renewable resources through synergies that occur, and may be more profitable than crop or livestock systems alone. Integrated crop/livestock research is complex, because of all the interactions that occur, and can only be accomplished through a multidisciplinary team research program. Practical considerations when developing an integrated crop/livestock research program include:

1. Scientists need to communicate and function as a true team.
2. Project responsibilities and manuscript preparation associated with the research program need to be discussed at the onset.
3. Negotiations and compromises may be necessary on the experimental design, number of treatments and replications, land area per treatment, and animal numbers.
4. Scientists who usually work within a specialty area may need to move outside their comfort zone to solve problems.
5. Statistical analyses may be challenging and require new and unusual approaches since interactions may be more important than the main effects.
6. Crops and crop sequences are critical to cropping system sustainability and for optimum use of precipitation.
7. Cropping systems need to be developed based on the needs of the animal species, type and class that are used.
8. Animals and cropping systems need to complement each other.

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Book Review

Long-term Field Experiments in Organic Farming. Edited by Joachim Raupp, Carola Pekrun, Meike Oltmanns and Ulrich Köpke. 2006. International Society of Organic Agriculture Research (ISOFAR), ISOFAR Scientific Series 1, Verlag Dr Köster, Berlin, Germany. 204 p. 25 Euros, ISBN 3-89574-590-1.

The arrival of *Long-term Field Experiments in Organic Farming* signifies a coming of age for the burgeoning organic farming research community. Results from some of the older experiments—on the productivity of organic systems and their potential for energy reduction, carbon sequestration and other social benefits—have made a splash in mainstream science journals in recent years, and interest among researchers is up. This book pulls together reports from a large selection of the long-term organic field experiments for the first time, highlighting their origins, objectives and important findings in an especially lucid way.

This book is both a wonderful introduction to these long-term experiments and a valuable reference for those who are already familiar with them. The book opens with a short preface, and then 12 selected organic field experiments are presented in alphabetical order. The experiments in this compilation are being conducted in Austria, Denmark, Germany, Israel, Italy, Switzerland and the United States—representing a diversity of soils and climatic conditions—and range from just a few years old to nearly three decades old. Although this compilation lacks any internal structure guiding readers on how these experiments have varied over time and across continents, each experiment report is brief, stylistically similar and easy to read.

The reports on these experiments emphasize the need for long-term research to understand the ecological processes in agriculture, particularly in organic farming systems. For example, the Danish report on a crop rotation experiment indicates that fertility building using organic practices requires 'a long-term integrated approach, rather than the short-term and targeted solutions common in conventional agriculture ... It follows that, for studies of management effects on soil fertility, long-term cropping experiments are indispensable.'

Many of these experiments are collecting data on an exceptionally large number of variables, including soil properties (such as pH, organic matter, inorganic and total N, carbon dioxide, fungi and bacteria), weed populations, insect dynamics, plant growth, biomass, yield, energy use and economic performance. Grain and oilseed crops are the major focus of most of these experiments, but quite a few also have potatoes in the cropping system rotation, and one includes cabbage. Only one of the 12 long-term experiments, the experiment in Israel that compares fertility strategies for peaches, focuses exclusively on a specialty crop.

Three of the oldest experiments—one in Switzerland and two in the United States—compare several organic systems (manure- and legume-based) with a conventional system (synthetic fertilizer and herbicide-based), and report the most comprehensive findings in this book. The FiBL Research Institute of Organic Agriculture in Switzerland began the first long-term organic experiment in 1978, examining wheat, potatoes, corn, grass–clover and other crops in long rotations. The two experiments in the United States, started by the Rodale Institute in 1981 and by the University of Minnesota in 1989, both examine soybeans as well as corn, hay and other crops in rotations of varying lengths. In the FiBL experiment, mean yields of all seven crops during a 28-year study period averaged 80% of those in the conventional systems, while organic yields in Minnesota experiment were somewhat closer to conventional and the Rodale experiment found that overall organically managed crop yields could equal those from conventional systems.

These three experiments also included findings on soil properties, indicating that the organic systems had higher soil carbon content, decreased nitrate leaching and increased soil fungi during the study period. The Rodale experiment report illustrated the importance of these findings: 'If the 64 million hectares of conventional maize and soybean in the U.S. were converted to organic production, the transition would likely allow the U.S., to meet the Kyoto Accord greenhouse gas reduction targets (assuming no other increases in C emissions develop), as well as save energy by reducing use of synthetic fertilizer and pesticides.'

The late seventies and 1980s were a period of expanding interest in organic agriculture, and these earlier experiments were developed to fill a scientific void on this topic by providing direct comparisons of conventional and organic farming systems. Some of the newer experiments featured in this compilation have focused exclusively on organic farming systems, and are no longer including conventionally managed plots. The book includes three experiments begun in the mid-1990s, one in Denmark and two in Germany, which examine alternative crop rotations, biodynamic amendments and other variations of organic management. Another experiment in Denmark tests the potential for recycling nutrients from urban waste streams, including human urine (which is not currently allowed in organic farming systems) on stockless organic farms.

One of the strengths of this book is the inclusion of experiments from numerous countries. One interesting difference between countries in Europe and the United States is that most of the long-term experiments being developed in the United States still include a conventional trial, perhaps because the need still exists to document the benefits of organic farming. In Europe, a

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political consensus developed over a decade ago to provide direct financial support for organic farming, and Europe has the highest adoption rates in the world for organic farming—in Italy, for example, 8% of agricultural land was under organic management in 2004. The United States has not yet developed a similar political consensus, and only 0.5% of the farmland in the United States is currently under organic management.

Nonetheless, the research focus of many of these long-term organic field experiments has broadened over time in experiments based in the United States as well as Europe. Some of the older experiments have added new research elements, such as food quality studies, and some of the more recently developed experiments are including a broader swath of the agricultural landscape in the study. An experiment that was established in 1994 in North Carolina—as a partnership between several universities and the North Carolina Department of Agriculture—is examining five diverse systems. In addition to conventional and organic cropping systems, this experiment is also examining a plantation forestry/woodlot system because of the predominance of woodlots on farms in the American South, and a successional ecosystem in an old field as a control for comparing the environmental impacts among farming systems. Similarly, a project developed in Austria in 2003 has a focus on improving the biodiversity of organic farming systems and is examining stockless organic and conventional crop rotations, and has also had included trials to measure the influence of hedges and other existing biotopes at the field margin.

The transition from organic to conventional production is still an important research feature in many of these long-term experiments. A 2003 project in Italy, at the University of Pisa, is comparing the long-term characteristics of organic and conventional cropping systems in a Mediterranean climate, and has imbedded 'playground' trials—on cover crop performance, cultivar performance and other topics—to provide quick-turnaround practical information to farmers as well as improve the experimental design. The North Carolina experiment and others have similarly nested short-term studies within the context of the overall experiment.

Important features of some of the long-term organic field experiments do yet appear to be standard. Only about half of the long-term experiments included in this volume appear to be collecting data on production costs, net returns and other indicators of the financial performance of organic systems. The Minnesota experiment report includes results from its economic analysis of organic and conventional systems, and illustrates the importance of including these indicators in the experiment. While the organic crops did not yield as high as the conventional crops, production costs were lower in the organic systems. And net returns for organic systems were equal to conventional systems without price premiums, and higher with premiums.

The shortcomings of this book are mostly stylistic. The book is a compilation of long-term organic field experiment reports, rather than an evaluation of this research. An executive summary would still have been a useful feature, as would a glossary of agricultural terms, which differ from country to country. The advantage of having a compilation of reports is that the focus of the book remains on the fascinating details of these experiments.

Long-term Field Experiments in Organic Farming is a useful— and inspiring—first offering on this topic from the International Society of Organic Agriculture Research (ISOFAR). In the foreword, Ulrich Kopke, the president of ISOFAR, writes that he hopes this book will attract 'widespread interest and might contribute to the cooperation of scientists, possibly even in a joint research project which assembles existing field trials.' A large, thorough evaluation of long-term organic field trial research is needed. This book is the perfect springboard for a more ambitious effort to tell a larger story—based on the analytical rigor of these experiments—about the sustainability of organic farming systems.

Catherine Greene, Resource and Rural Economics Division, Economic Research Service, USDA.
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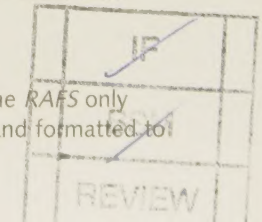

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